Division of Engineering Laboratories
Hydraulic Laboratories Branch

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF ANCHOR DAM (EARTHFILL) TUNNEL SPILLWAY AND OUTLET WORKS

Hydraulic Laboratory Report No. Hyd-437

DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

May 28, 1957

CONTENTS

CONTENTS--Continued

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Commissioner's Office--Denver
Division of Engineering Laboratories
Hydraulic Laboratory Branch
Hydraulic Structures Section
Denver, Colorado
May 28, 1957

Laboratory Report No. Hyd-437
Compiled by: G. L. Beichley
Checked by: A. J. Peterka
Reviewed by: J. W. Ball
Submitted by: H. M. Martin

Subject: Hydraulic model studies of Anchor Dam (earthfill) tunnel spillway and outlet works

SUMMARY

Hydraulic model studies of Anchor Dam (earthfill) tunnel spillway, the outlet works tunnel, and the junction of the outlet works tunnel with the spillway, Figures 1 through 7, inclusive, were conducted on a 1 to 15.8 scale model, Figures 8 through 13, to develop the hydraulic design.

Data and notes taken on the flow in the model showed the general concept of the preliminary structure to be satisfactory but that certain modifications in the approach channel, in the outlet works tunnel junction with the spillway tunnel, and in the horizontal bend of the spillway tunnel were desirable. Better flow distribution and less turbulence at the spillway entrance were gained by modification of the approach channel, Figures 14 through 17. Less likelihood of subatmospheric pressures, which might cause cavitation erosion, can be accomplished in the outlet works tunnel junction with the spillway by placing a 6-inch-radius chamfer on the edges joining the two tunnels, Figures 5, 22, and 37 through 40. To maintain an air passing through the tunnel and to prevent possible choking and filling of the tunnel, a guide vane was provided along the tunnel crown through the horizontal bend and downstream to Station 11+15, Figures 3, 24, 25, and 26.

Other model data showed other aspects of the preliminary design to be satisfactory. For example, all transitions in the tunnels were found to be satisfactory, the vertical curvature of the outlet works tunnel was not too sharp, the radius of the vertical bend in the spillway tunnel as well as the tunnel size was ample, the stilling basin including the flip bucket end sill was satisfactory.

Motion pictures were made of the recommended structure discharging design capacities. The pictures include closeup views of the component parts of the structure as well as an overall view.

INTRODUCTION

Anchor Dam is part of the Missouri River Basin Project. It is located on Owl Creek about 30 miles west of Thermopolis, Wyoming, Figure 1. One plan, Figures 2 through 7, considered an earthfill structure approximately 370 feet long and 190 feet above the riverbed. The plan includes a spillway and an outlet works, Figure 2, which was modeled and tested, Figures 8 through 13. The spillway is designed to discharge 7,340 second-feet at maximum reservoir elevation 6460.5. The outlet works is designed to discharge 640 second-feet.

Normally the outlet works is to be controlled to discharge 300 second-feet. The outlet works and spillway are not designed to discharge simultaneously except when the spillway first begins to spill water.

The spillway, Figure 3, located in the right abutment consists of a concrete-lined horseshoe tunnel. A concrete-lined horseshoe outlet works tunnel joins the spillway tunnel in the vertical bend of the spillway tunnel, Figure 4. The spillway crest at elevation 6441 is 5 feet above the approach channel floor, 19.5 feet below the maximum reservoir, and 165 feet above the discharge channel in the riverbed. The approach channel is excavated 17.5 feet wide with 1 on 1 side slopes. At Station 3+86.25 it joins a concrete apron extending 13.75 feet upstream from the crest section at Station 4+00, Figure 5. The apron is bounded by two curved approach training walls that slope upward at the rate of 1 on 1/4. These training walls continue along each side of the spillway crest section and join the tunnel entrance portal at Station 4+19.5 on the invert.

From Station 4+19.5 to Station 4+30.60 the invert of the tunnel drops 10.77 feet and the tunnel transitions from a 20-foot-diameter tunnel to a 17-foot-diameter horseshoe shape. Then the tunnel tapers from a 17-foot-diameter to a 12-foot-diameter horseshoe down a 50° incline to Station 5+21.37 at elevation 6315.427. Here the tunnel bends on a 93.75-foot radius to a slope of 0.006 at Station 5+92.624. The 12-foot-diameter horseshoe tunnel continues on this slope to Station 11+15, Figure 3. From Station 9+45 to Station 9+75 the tunnel bottom changes from a horseshoe shape to a flat bottom. From Station 9+98.66 to Station 10+85.93 the tunnel follows a 25° horizontal bend along the arc of 200-foot radius.

At Station 11+15 the flat bottom follows a trajectory curve downward 12.75 feet to the stilling basin floor at Station 11+95 at elevation 6266.06, Figure 6. At Station 12+55 the horizontal floor of the basin curves upward on an arc of 100-foot radius to elevation 6276. At Station 13+00, 18-3/8 inches downstream from the end of the arc, the basin terminates in the river channel at elevation 6276. The river channel is riprapped around the end of the basin and for 20 feet downstream.

The outlet tunnel joins the spillway tunnel in the vertical bend as shown in Figure 4. The flow from the outlet works is controlled by two 2-foot 3-inch-square, high pressure slide gates, Figure 7. Between the gates is a 3-foot 4-1/2-inch-high pier that extends 20 feet into the 6-foot 9-inch-diameter concrete-lined tunnel. The bottom half of the tunnel transitions from a square shape at the upstream end of the pier to a horseshoe shape 4 feet downstream from the end of the pier. The tunnel slopes downward 10° and is vented at the upstream end by an 18-inch outside-diameter inlet pipe. At 8.27 feet downstream from the end of pier the tunnel bends downward on a 70-foot parabolical, vertical curve and begins to taper from a 6-foot 9-inch-diameter horseshoe tunnel to a 6-foot-diameter horseshoe. At the P.I. of the vertical curve, the tunnel is 6 feet in diameter and continues to the spillway tunnel. A tangent 11.29 feet long connects the invert of the vertical curve at the P.T. to the invert of the spillway tunnel bend, Figure 5. A deflector 3 feet long and 6 inches high at the invert is installed across the spillway tunnel just above the outlet tunnel opening to deflect spillway flows over the outlet tunnel opening.

THE MODEL

The model was a 1 to 15.8 scale reproduction of the spillway and surrounding area including the outlet works control gates and tunnel that extended from the gates to the spillway tunnel, Figures 8, 9, 10, 11, 12, and 13. The model consisted of four main parts: (1) the reservoir area surrounding the spillway entrance; (2) the spillway structure consisting of the crest, the tunnel, and the stilling basin; (3) the tail water area consisting of the discharge channel and river channel extending downstream from the spillway stilling basin; and (4) the outlet works structure consisting of the control gate chamber and the tunnel from the gates to the spillway tunnel junction.

Reservoir

The reservoir was contained in a head box, Figure 9, which allowed reproduction of the topography for approximately 150 feet upstream from the spillway crest and approximately 65 feet to the right and 75 feet to the left of the spillway center line. The floor of the box was at elevation 6404 and the top of the box at elevation 6467.

Topography in the reservoir area was modeled of concrete mortar placed on metal lath which had been nailed over wooden templates shaped to the ground surface contours. The surface was given a rough finish to simulate the natural topography of the prototype. The cut surfaces of the approach channel were given a smooth finish.

Spillway Structure

Crest section. The crest, Figure 9b, was molded in cement mortar. Sheet metal templates accurately cut and placed were used as guides. Piezometers along the tunnel center line in the spillway crest consisted of 1/16-inch inside-diameter brass tubes soldered at right angles to the profile shape of a template and filed flush.

Tunnel. The spillway tunnel from the crest to the horizontal bend was molded completely in transparent plastic, Figures 8 and 10. Wood patterns were accurately shaped for use in molding the plastic tunnel sections from flat sheets. The plastic tunnel sections were flanged and bolted together using waterproof grease between flanges to prevent leakage. Plastic piezometers having a 1/16-inch inside-diameter hole were inserted where needed to measure pressures.

The horizontal bend portion of the tunnel was constructed on a wood platform which provided the floor of the tunnel, Figure 10c. The vertical sides of the tunnel and the round top were made of transparent plastic sheets sealed to the platform. Three wood flanges were used to strengthen and hold the plastic tunnel in place.

Stilling basin. The stilling basin, Figure 11, was constructed of 5/8-inch plywood which was given a resin coating to prevent warping. The roof of the basin was omitted in the model to facilitate observing and recording model data. The curved trajectory floor and the curved sill at end of basin were constructed of sheet metal placed over wood templates. Piezometers having a 1/16-inch-diameter hole were installed on the trajectory curve for measuring pressures.

Downstream Area

A length of river channel extending approximately 250 feet downstream from the end of the stilling basin was reproduced in the model. It was constructed of concrete in the same manner as was the reservoir topography, Figure 11. Stones 1-1/2 inches to 2-1/4 inches in diameter were used in the discharge channel at the end of the basin to simulate prototype riprap 2 to 3 feet in diameter.

Outlet Works Structure

Tunnel upstream from the gate structure. Only the outlet works control gates and the section of tunnel between the gates and the spillway tunnel were reproduced to scale in the model, Figure 10. A 6-inch sheet metal pipe upstream from the control gates conveyed the outlet works flow from the reservoir to the control gates. Immediately upstream from the gate structure, two sheet metal transition sections transformed the 6-inch-round pipe to a rectangular section that fit the two square gate tunnels, Figures 10b and 12. In the transition section joining the plastic gate structure, a tapering sheet metal pier nose was soldered in place to direct the flow smoothly into each of the two gate tunnels.

Gate structure. The gate structure shown in Figures 10b and 12 was constructed of transparent plastic. The slide gates were operated by means of brass rods threaded 8 turns to the inch.

Tunnel downstream from the gate structure. The tunnel from the gate structure to the spillway tunnel, Figure 10b, was molded in transparent plastic in the same manner as the spillway tunnel. The dividing pier extending downstream from the gate structure into the tunnel was constructed of wood and coated with a resin to prevent warping.

The downstream end of the outlet works tunnel was joined to the spillway tunnel as shown in Figure 13. The deflector on the invert of the spillway tunnel and a section of the spillway tunnel bottom extending upstream were made as a removable piece so that the size of the deflector could readily be changed for model testing if so desired.

Hydraulic Losses

In a model it is often difficult to reproduce the friction head losses to scale since the model surfaces over which the flow passes usually do not represent the prototype roughness to scale. Therefore, it is usually necessary to adjust the length or slope of the model spillway so that the velocity of the flow will be reproduced to scale as it enters the stilling basin.

Since the stilling basin was designed primarily to retain the hydraulic jump for the maximum outlet works discharge, the outlet works tunnel in combination with the spillway tunnel was used for determining if a model adjustment was necessary. To determine the adjustment required, if any, the velocity and depth of flow at the beginning of the stilling basin trajectory, Station 11+15, were computed for both the model and the prototype. In the prototype it was assumed that the roughness coefficient, "n," had a value of 0.008 in the outlet works tunnel and a value of 0.013 in the spillway tunnel. Using these assumptions, the velocity at Station 11+15 for the maximum outlet flow of 640 second-feet was computed to be approximately 24 feet per second. In the model the roughness coefficient for the plastic was assumed to have a value of 0.008 in both the outlet works and spillway tunnels, and the model velocity at Station 11+15 was computed to be 6.12 feet per second for a model discharge representing 640 second-feet in the prototype. Since the model velocity represents a prototype velocity equal to the model velocity multiplied by the square root of the model scale, 6.12 feet per second represents a prototype velocity of approximately 24 feet per second. Therefore, if all assumptions are correct, no adjustment in length or slope of the tunnel is required. However, to provide a factor of safety and because of space limitations in the laboratory, the model tunnel length was reduced 6 feet. Therefore, 6 feet of the straight model spillway tunnel between the vertical bend and the horizontal bend were not constructed.

THE INVESTIGATION

The primary purpose of the investigation was to develop the hydraulic design of the spillway structure including the junction of the outlet works structure with the spillway structure. In developing the spillway design, it was necessary to study the characteristics of the flow as it approached and passed through the spillway as well as the characteristics of the flow as it entered and flowed through the river channel. In developing the junction of the outlet works tunnel with the spillway tunnel, it was necessary to study the flow with the outlet works and spillway discharging separately and with both discharging simultaneously.

Spillway Entrance

Approach channel. The approach channel to the spillway was adequate to discharge all flows up to and including the design discharge, Figure 14; however, it was felt that for discharges near the design limit the flow conditions could be improved by reshaping the approach channel. It was felt that rounding the edges along the top of the cuts on both sides of the channel would reduce disturbances that originated at these edges. However, to show the ultimate improvement possible, more drastic alterations were made.

Confetti scattered on the model water surface shows that the flow approached the spillway entrance from the left, Figure 14. As a result, the water surface at the entrance sloped upward from left to right. For 7,150 second-feet the water surface near the left training wall was depressed about 2 feet which uncovered a boil along the left wall apparently caused by submerged currents flowing into the training wall. The water surface near the right training wall was relatively high, and no boil was evident.

To remedy this situation, it was believed that the approach channel floor should curve from the left in line with the direction of flow shown in Figure 14 or that the left bank of the approach channel should be cut down as much as practical. It was decided to test the latter, Figure 15, first.

The top of the left approach bank at the top of the training wall, elevation 6467, Figure 15a, was moved back 14 feet and sloped downward 2 on 1 toward the center line of the channel until it intersected the preliminary 1 on 1 slope.

For 4,000 second-feet, the improvement in flow conditions was slight, but for 7,150 second-feet the improvement was considerable as shown by comparison of Figures 14c and 15c. Only a slight boil could be observed along the left training wall, and the water surface was more nearly level across the spillway entrance. The capacity of the spillway was probably increased a small amount although tests were not made to prove this. This modification is recommended for the prototype.

Tunnel entrance. The recommended approach channel also improved the flow conditions at the tunnel entrance as shown by comparison of Figures 16 and 17. The flow was more uniformly distributed in the tunnel after the recommended approach was installed.

Pressures were recorded for discharges of approximately 1,000 and 7,200 second-feet in the tunnel entrance at the piezometers shown in Figure 18. All the piezometers except No. 52 are located in the transition section, Figure 5. Piezometers 51 and 52 are also shown in Figure 17c. All pressures recorded were atmospheric or above except for a slight subatmospheric pressure at Piezometers 51 and 52. In Figure 17c, the flow could be seen to separate from the transition walls just upstream from the piezometers. This is probably the reason for the subatmospheric pressures. Since the subatmospheric pressures are less than 1 foot of water, no serious consequences such as cavitation erosion are expected. The transition section as preliminarily designed is recommended for the prototype.

Spillway crest. The spillway model was calibrated to determine its capacity for reservoir elevations up to and including reservoir design elevation 6460.5 feet. The calibration curve showed slightly less discharge than the curve used for design, Figure 19. At design reservoir elevation the spillway capacity was measured to be 7,200 second-feet which is sufficiently close to the design capacity of 7,340 to recommend approval of the crest shape.

Based on a crest length of 20 feet, the discharge coefficient curve was computed from the calibrated curve and is shown in Figure 19. For the design head, the coefficient, 4.15, is quite large because the training walls are battered, 1/4 to 1, which in effect lengthens the crest beyond 20 feet, Figure 5.

For discharges of 1,000 and 7,150 second-feet, pressures were measured on the crest profile along the center line of the spillway, Figure 20. All pressures were above atmospheric. Therefore, the preliminary design of the crest shape is recommended for the prototype.

Spillway Tunnel

Flow conditions at the tunnel entrance have been discussed in a preceding section. Flow conditions throughout the inclined tunnel, the vertical bend, and the nearly horizontal portion will be discussed in this section and are shown in Figures 21, 22, 23, and 24 for discharges of 1,100, 4,000, and 7,150 second-feet in the preliminary tunnel design.

Flow down the incline and through the nearly horizontal portion was straight and uniform as shown in Figure 21. For the design discharge the tunnel was about two-thirds full at the lower bend. Immediately downstream from the bend the water surface cross section was dished slightly as the centrifugal force of the flow passing around the bend caused the water to climb the sides of the tunnel. Flow conditions were excellent, however, and the tunnel was still plenty large to handle the design flow.

The flow passed over the outlet tunnel opening in a very satisfactory manner for both small and large discharges, as shown in Figure 22. The performance at this junction will be discussed more fully in the section "The Outlet Works Tunnel and Spillway Tunnel Junction."

Flow through the horizontal bend was satisfactory for small flows, as shown in Figure 23, but was not considered to be good for the larger discharges from 4,000 second-feet on up, as shown in Figure 24. As the flow passed through the bend, the water climbed the outside wall until, for the design flow, it spiraled over the top and down the other side, virtually closing the tunnel at the stilling basin entrance at Station 11+15. Flying particles of water filled the end of the tunnel at the basin entrance in the model. More spray will occur in the prototype than is shown by the model; therefore, it was believed that remedial measures should be taken to provide an air passage, free from spray, throughout the tunnel. Without the guarantee of an air passage at all times during operation, it was feared that the tunnel might momentarily choke, then fill, and create surges in the flow.

It was recommended that the bend be eliminated or its radius greatly increased. However, because of steep talus slopes and lack of rock foundation the tunnel location could not be changed.

The alternative was to install a guide vane, Figure 25, along the crown of the tunnel throughout most of the horizontal bend and extend the vane as far as the stilling basin entrance. A guide vane 16 inches thick by 32 inches deep, beginning at approximately one-third of the arc length and extending to the basin entrance, was installed in the model.

The vane was effective in providing an air space through the bend to the basin entrance by preventing the flow from spirling over the top of the tunnel as shown in Figure 25. The vane was recommended for the prototype.

Water surface profiles for the design discharge were measured at various sections throughout the tunnel and are shown in Figure 26. These profiles show the tunnel with the guide vane to be adequate.

Stilling Basin

Acting as a hydraulic jump basin. The stilling basin operating as a hydraulic jump basin is shown in Figures 27, 28, and 29. The basin was more than adequate in discharging the outlet works' normal flow of 300 second-feet and the outlet works' design flow of 640 second-feet. In fact, tests showed that the basin retained the hydraulic jump for discharges up to and including 1,400 second-feet when the discharge was increasing, though, once the jump swept out, it did not fall back into the basin until the discharge was decreased to approximately 640 second-feet.

Water surface profiles and cross-sectional depths measured in the basin are shown in Figure 30. The flow entering the jump was not always uniformly distributed across the width of the basin because the flow from the horizontal bend did not provide uniformly distributed flow at the basin entrance, Station 11+15. However, uniform flow depth at the toe of the jump was not necessary to provide adequate performance since the basin was narrow and longer than the jump length for discharges up to about 1,000 second-feet, as shown in Figure 30.

The river channel at the end of the basin was to be riprapped, as shown in Figures 3 and 11, so erosion tests were conducted to determine the size of riprap needed. Most of the stones in the model riprap represented prototype stones 2 feet in diameter, however, some were as large or larger than the 3-foot size specified.
The riprap bed prior to testing in the model was at elevation 275 which is 1 foot below the elevation specified for the prototype.

For the outlet design discharge, 2-foot stones were moved out of the riprap bed, eroding the bed to elevation 270 in a 20-minute model test run as shown in Figure 31. This test indicated that 3-foot stones or larger were required. Without replacing eroded riprap, the discharge was increased to 1,400 second-feet. Nearly all of the stones in the bed, including some 5 feet in diameter, were washed away in a 20-minute model run as shown in Figure 32. It was believed that much larger stones were available nearby in the river channel so it was recommended that many large stones 5 feet and larger in diameter, be used in the prototype.

Acting as a flip bucket. For larger discharges the basin was designed to act as a flip bucket. When the hydraulic jump was swept out of the basin, the end sill became a bucket to pitch the flow into the river channel away from the structure. The basin operating as a flip bucket for large discharges is shown in Figure 33 and for smaller discharges in Figure 29.

It was concluded from observation of the model that the jet from the prototype basin would probably erode a considerable quantity of material from the riverbanks, particularly at the bend in the river downstream. Erosion of the riverbanks in itself was not considered to be as harmful as the deposition of eroded material in the river channel. Deposits might create a dam that would back up small flows and submerge the tunnel. However, the river channel is quite steep and the velocity high so it was believed that material would not be deposited in the bed until it had traveled far enough downstream that no damming effect would be felt at the tunnel portal.

Because the flow was concentrated on the left side of the tunnel after passing through the horizontal tunnel bend, Figures 25 and 26, the flow zigzagged through the basin as shown in Figures 33 and 34. Flow was concentrated along the right wall at the end of the basin and, therefore, produced an unsymmetrical jet leaving the flip bucket. However, the jet was not considered to be objectionable. The unequal distribution at the end of the basin produced greater forces on the right training wall than on the left. For the maximum discharge, the distribution was much more even and the jet was more symmetrical.

Jet measurements for the design discharge were made and are recorded in Figure 35. It was found that the jet was not projected as far downstream from the basin as was anticipated. This was not objectionable in any way, however. It was believed that the principal reason for the shorter trajectory was that the hydraulic losses in the horizontal bend and stilling basin were greater than anticipated.

Pressures along the basin entrance trajectory center line were measured and are recorded in Figure 36 for discharges of 7,150 and 1,000 second-feet. No subatmospheric pressures were found, therefore, the shape of the trajectory was satisfactory for the prototype as preliminarily designed.

The tests and observations of the stilling basin operation, both as a hydraulic jump basin and as a flip bucket, showed the basin to perform satisfactorily, and the preliminary design of the basin is recommended for the prototype.

The Outlet Works Tunnel and Spillway Tunnel Junction

The flow from the outlet works is controlled by two slide gates shown in the model, in Figures 10, 12, and 37. The normal outlet works discharge is 300 second-feet. The design discharge for maximum reservoir elevation with 100 percent gate opening is 640 second-feet.

The model gates were capable of discharging more than 640 second-feet, however, because of the larger-than-scale approach pipe that was used. The model could discharge 640 second-feet with the gates either 100 percent open and the reservoir at approximately elevation 6430 or with the gate opening reduced to 87 percent and the reservoir at approximately spillway crest elevation 6441. This latter condition is on the side of safety for some test purposes since a slightly higher velocity occurs in the model than in the prototype. Performance for this flow condition is shown in Figure 37. Flow entered the spillway tunnel in a very satisfactory manner.

Normal discharge of 300 second-feet is also shown in Figure 37 and appeared to be very satisfactory. The gates are open 49 percent to hold the reservoir at spillway crest elevation.

The outlet tunnel was vented by an 18-inch pipe located in the outlet tunnel just downstream from the gates, Figure 7. For both 300 and 640 second-feet a considerable amount of air was drawn through the vent and through the inclined tunnel of the spillway. Closing the vent appeared to have no effect on the flow. This was probably because air could enter the outlet tunnel from the inclined tunnel at the junction of the two tunnels. This may or may not be possible in the prototype because of increased spray and bulking of the outflow.

The outlet works tunnel and the spillway tunnel could be operated jointly for flows up to 4,000 second-feet, and the performance was very good, Figure 38; however, the outlet works and spillway were not designed to operate simultaneously except when the spillway first begins to discharge. In this case the outlet works tunnel would discharge about 640 second-feet and the spillway tunnel about 500 second-feet more or less. Such a discharge combination, Figure 38, appeared to be very satisfactory.

The air vent appeared to be sufficiently large. It supplied a relatively large quantity of air. However, closing the vent did not change flow conditions in the outlet tunnel but did cause a little splash and spray in the spillway tunnel where the two flows joined.

When the outlet works tunnel vent was closed with the total flow of the two tunnels exceeding approximately 1,200 second-feet, the outlet works tunnel filled with water. Since the outlet works tunnel is not intended to operate as a pressure tunnel, it is recommended that the outlet works be closed when the spillway is discharging, except when the total discharge of the two does not exceed about 1,000 second-feet. This will also delay the sweepout in the jump basin and, in the case of a small flood, may even prevent the sweepout from occurring.

For spillway discharges near its design capacity, the outlet works, if operating, sometimes fills completely even though the vent is open. This is caused by a slight surge in the outlet works or spillway flow which might stop the flow of air in the outlet tunnel just long enough to choke the tunnel; the tunnel then fills and stays full of water. When the outlet works tunnel flows full, it causes spray in the spillway tunnel. The amount of spray, for a given outlet discharge and head, depends upon the thickness of the spillway flow passing over the outlet works portal. If the thickness is small, the spray is severe. This is not a recommended operating condition.

When the spillway alone is discharging, as shown in Figure 22, no splash or spray occurs at the junction. For all flows, water backs up into the outlet works tunnel. The elevation to which the flow backs up depends upon the discharge and is a measurement of the average pressure exerted on the outlet tunnel opening. The length and height of the deflector in the spillway tunnel, shown in Figure 5, govern to some extent the amount of water that is backed up into the outlet tunnel. The deflector as preliminarily designed is believed to be very satisfactory and is recommended for the prototype.

Pressures were measured at piezometers located near the invert of the outlet tunnel and are recorded in Figure 39 for the outlet works design discharge. The pressures were found to be close to atmospheric, therefore, the curvature of the tunnel invert as preliminarily designed is recommended for the prototype.

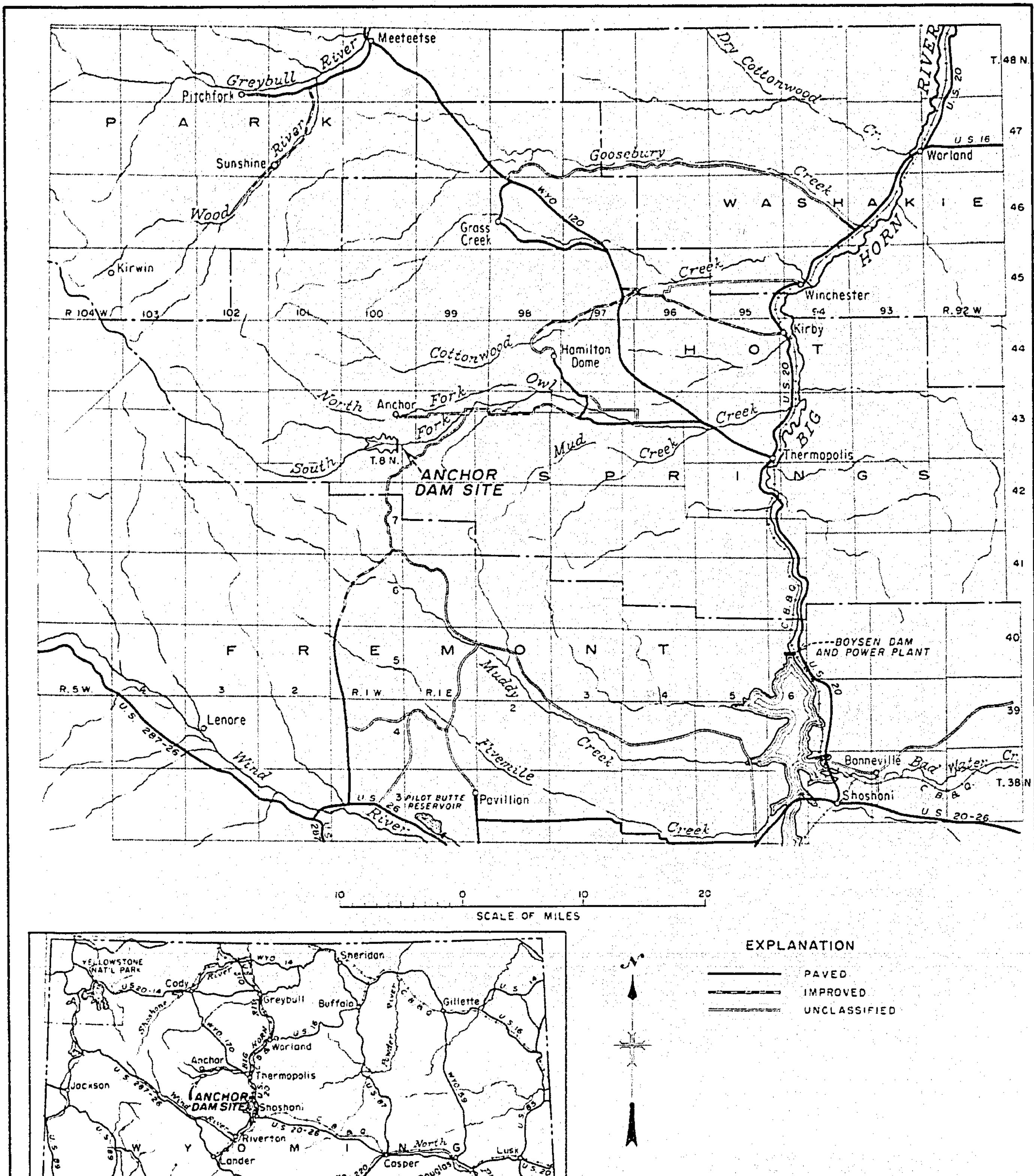
Pressures were also measured at the junction of the two tunnels at the piezometers shown in Figure 40. Most of these piezometers were located along the edges of the two joining tunnels. It was believed that subatmospheric pressures might exist here, particularly on the wall of the outlet works tunnel.

Lowest pressures were recorded when the outlet works was discharging. For 640 second-feet with gates 100 percent open, 5 feet of water below atmospheric was recorded at Piezometer 37, Figure 41. By increasing the head and reducing the gate opening to 87 percent which is not a true operating condition for the prototype, the subatmospheric pressure increased to 9 feet at Piezometer 42. Piezometers 37, 39, and 42 showed greater subatmospheric pressures than any of the others on the wall of the outlet tunnel because they were closer to the common edge of the tunnels. Therefore, the subatmospheric pressures right at the common edge might exceed 9 feet of water. Pressure at Piezometer 60 on the floor of the spillway near the common edge was 3.1 feet of water below atmospheric. It was, therefore, recommended that these edges be chamfered with a 6-inch radius as shown in Figure 5. It was believed that the rounded edges would result in higher pressures in the prototype than were measured in the model.

When the spillway alone was discharging large flows, air bubble swirls were observed in the outlet works tunnel, Figure 22c. The center of these swirls could have pressures below atmospheric, but if present may not reach the tunnel surfaces. A piezometer was installed in the most likely region, 6 feet upstream from Piezometer 41 near the outlet works tunnel invert, Figure 40. It showed the pressure to fluctuate from approximately zero to 5 feet of water above atmospheric. As a result of these tests, the junction section of the two tunnels as designed, plus the radius added to the common edges of the two tunnels, is recommended for the prototype.

ACKNOWLEDGMENT

The modifications to the Anchor Dam spillway and outlet structure, evolved from hydraulic model studies, were developed through the cooperation of the staffs of the Spillway and Outlets Section and the Hydraulic Laboratory. Wai-Han Cheng assisted in performing the laboratory tests.



UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
BIGHORN BASIN DIVISION-OWL CREEK UNIT-WYOMING

ANCHOR DAM
LOCATION MAP

DRAWN C.A.M. SUBMITTED T.V.B. Keener
TRACED B.F.W. RECOMMENDED W.H. Nalder
CHECKED E.L.A. J.J.H. APPROVED W.E. Blomgren ACT. CHIEF ENGINEER

DENVER, COLORADO, MARCH 27, 1950 339-D-106

FIGURE 2
REPORT HYD. 437

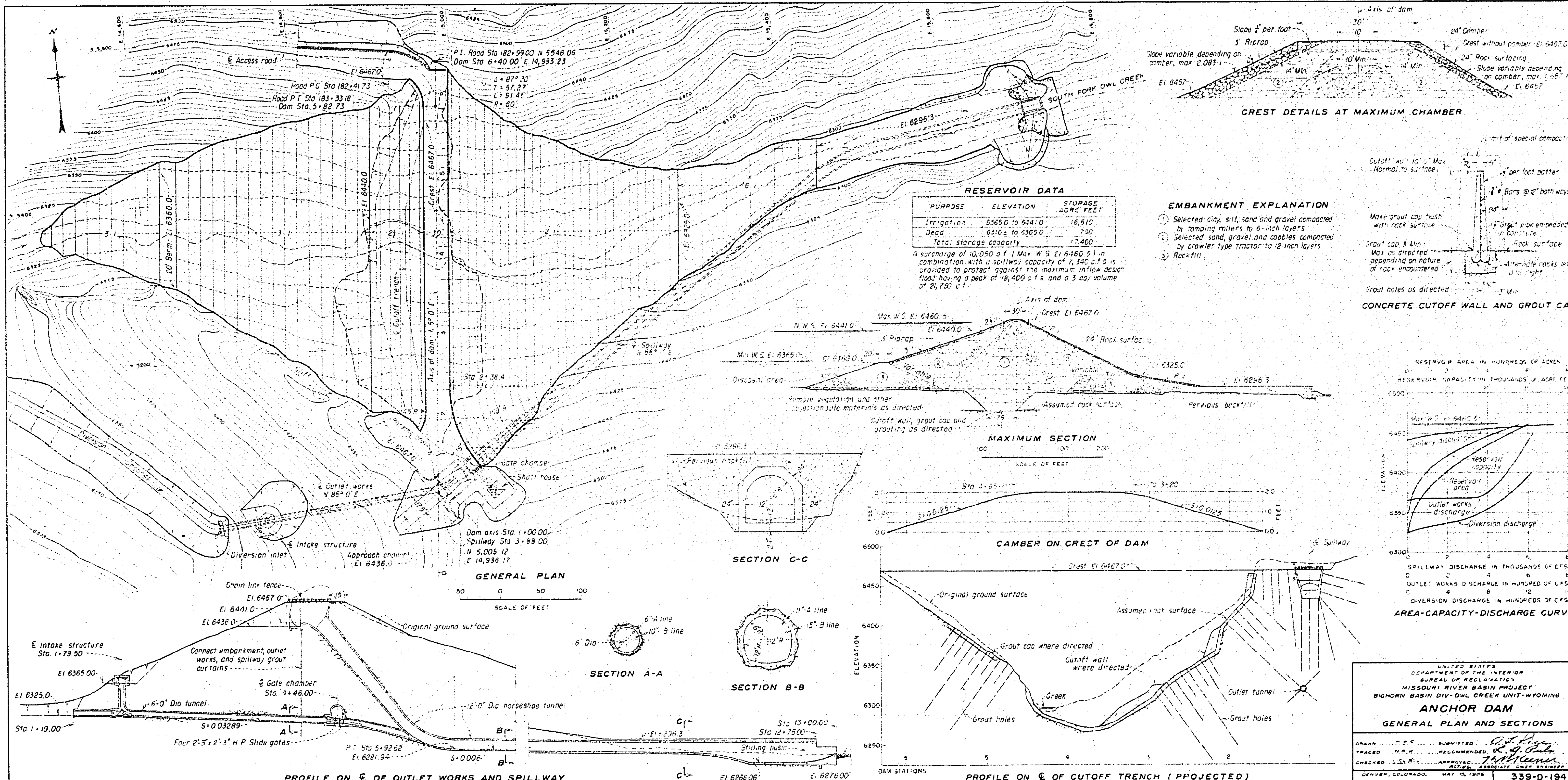
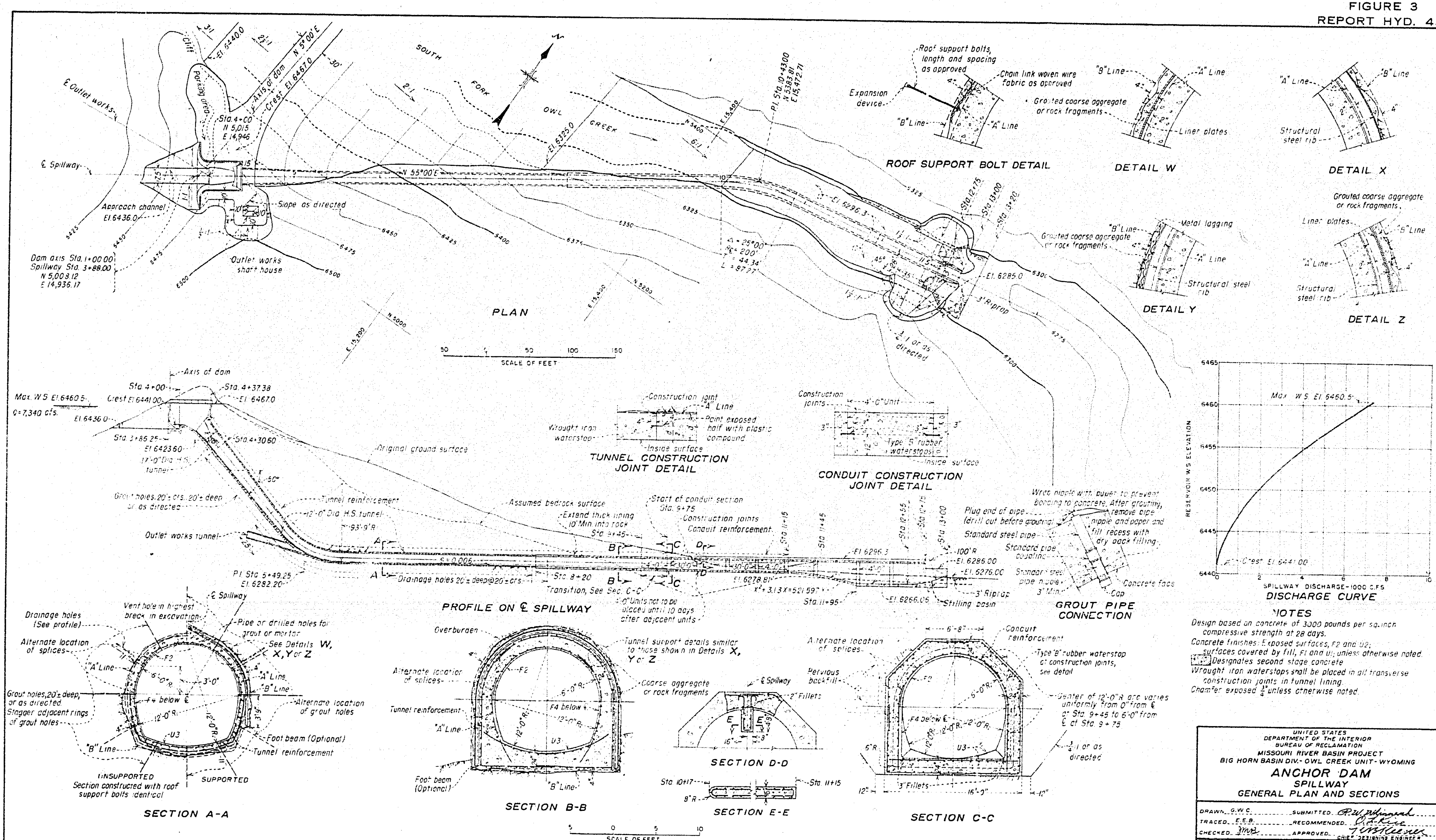
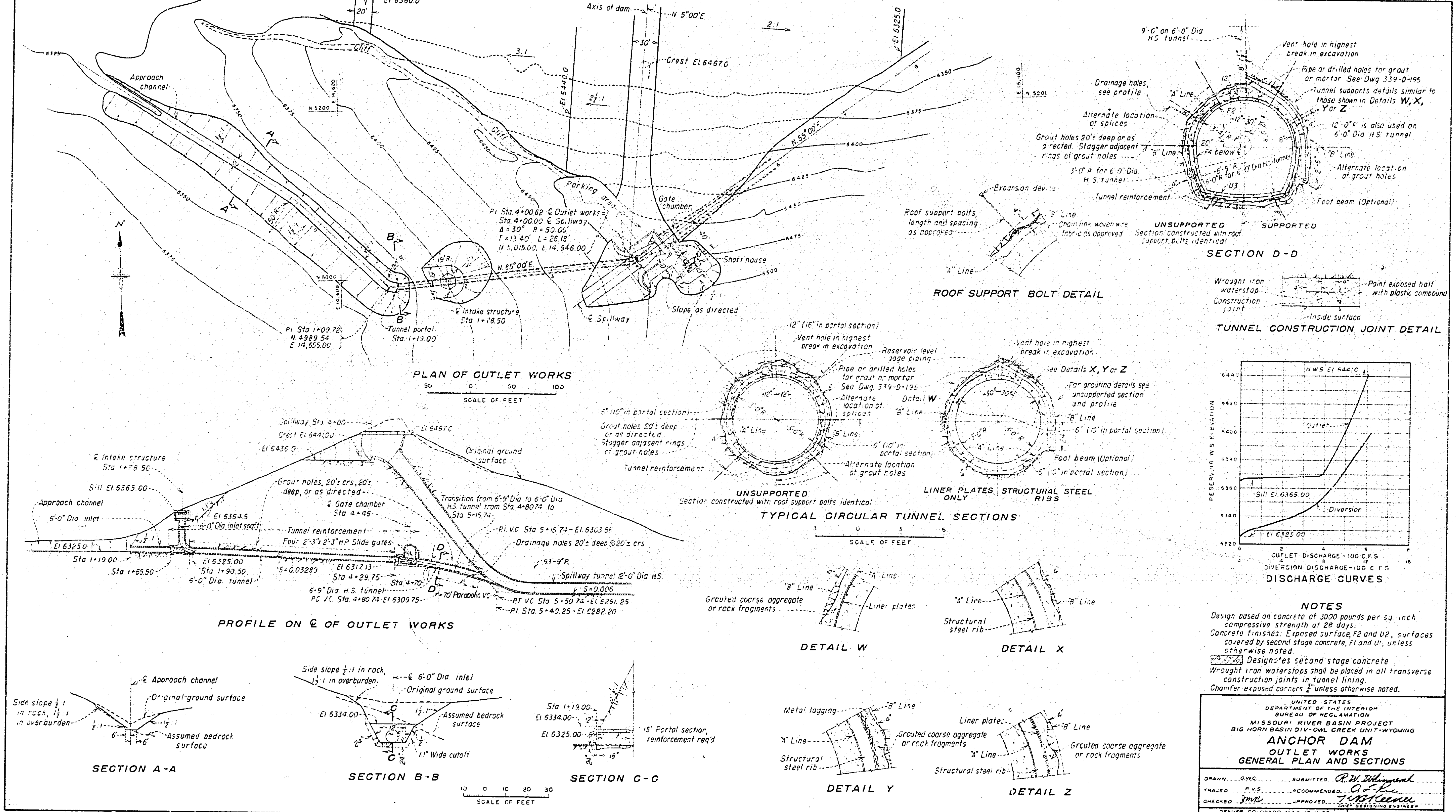
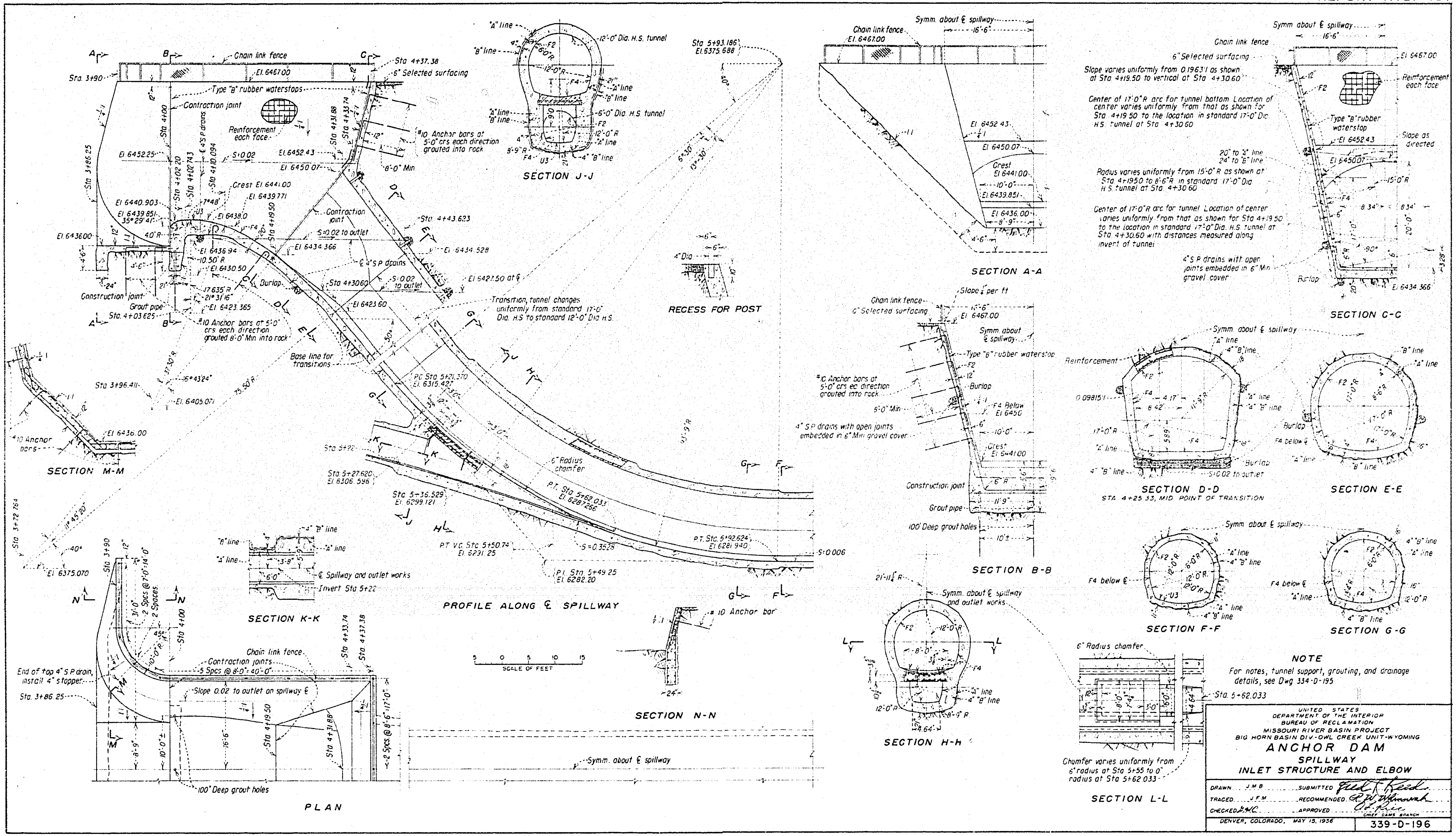


FIGURE 3
REPORT HYD. 437




PLAN OF OUTLET WORKS
SCALE OF FEET
Approach channel
Cliff
Axis of dam
N 5°00'E
Crest El 6467.0
Parking area
Gate chamber
Shaft house
N 55°00'E
N 85°00'E
Intake structure Sta. 1+78.50
Tunnel portal Sta. 1+19.00
Spillway
Slope as directed
PROFILE ON ℄ OF OUTLET WORKS
Spillway Sta 4+00
Crest El 6440.00
Original ground surface
℄ Intake structure Sta 1+78.50
Approach channel
6'-0" Dia inlet
El 6325.0
Grout holes, 20'± crs, 20'± deep, or as directed
℄ Gate chamber Sta 4+46
Tunnel reinforcement
Four 2'-3"x2'-3" HP Slide gates
Transition from 6'-9" Dia to 6'-0" Dia HS tunnel from Sta. 4+80.74 to Sta 5+15.74
Drainage holes 20'± deep @ 20'± crs
Spillway tunnel 12'-0" Dia H.S.
S = 0.006
S = 0.03289
5'-0" Dia. tunnel
6'-9" Dia. H.S. tunnel
70' Parabolic VC
SECTION A-A
SECTION B-B
SECTION C-C
15' Portal section, reinforcement req'd.
SCALE OF FEET
SECTION D-D
UNSUPPORTED
SUPPORTED
Tunnel reinforcement
Foot beam (Optional)
ROOF SUPPORT BOLT DETAIL
TUNNEL CONSTRUCTION JOINT DETAIL
Wrought iron waterstop
Construction joint
Paint exposed half with plastic compound
Inside surface
TYPICAL CIRCULAR TUNNEL SECTIONS
UNSUPPORTED
Section constructed with roof support bolts identical
LINER PLATES ONLY
STRUCTURAL STEEL RIBS
SCALE OF FEET
DISCHARGE CURVES
RESERVOIR W.S. ELEVATION
N.W.S. El 6441.0
Outlet
Diversion
Sill El 6365.00
El 6325.00
OUTLET DISCHARGE - 100 C.F.S.
DIVERSION DISCHARGE - 100 C.F.S.
DETAIL W
DETAIL X
DETAIL Y
DETAIL Z
Liner plates
Structural steel rib
Metal lagging
Grouted coarse aggregate or rock fragments
NOTES
Design based on concrete of 3000 pounds per sq. inch compressive strength at 28 days.
Concrete finishes: Exposed surface F2 and U2, surfaces covered by second stage concrete, F1 and U1, unless otherwise noted.
Designates second stage concrete.
Wrought iron waterstops shall be placed in all transverse construction joints in tunnel lining.
Chamfer exposed corners ¾" unless otherwise noted.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
BIG HORN BASIN DIV.-OWL CREEK UNIT-WYOMING
ANCHOR DAM
OUTLET WORKS
GENERAL PLAN AND SECTIONS
DRAWN
TRACED
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
CHIEF DESIGNING ENGINEER
DENVER, COLORADO, MAY 15, 1956
339-D-198


SECTION J-J
RECESS FOR POST
SECTION A-A
SECTION C-C
SECTION M-M
SECTION B-B
SECTION D-D
STA 4+25.33, MID POINT OF TRANSITION
SECTION E-E
SECTION K-K
PROFILE ALONG ℄ SPILLWAY
SECTION F-F
SECTION G-G
SECTION N-N
SECTION H-H
SCALE OF FEET
NOTE
For notes, tunnel support, grouting, and drainage details, see Dwg 334-D-195
SECTION L-L
PLAN
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
BIG HORN BASIN DIV.-OWL CREEK UNIT-WYOMING
ANCHOR DAM
SPILLWAY
INLET STRUCTURE AND ELBOW
DRAWN J.M.B.
SUBMITTED
TRACED J.F.M.
RECOMMENDED
CHECKED
APPROVED
CHIEF DAMS BRANCH
DENVER, COLORADO, MAY 15, 1956
339-D-196

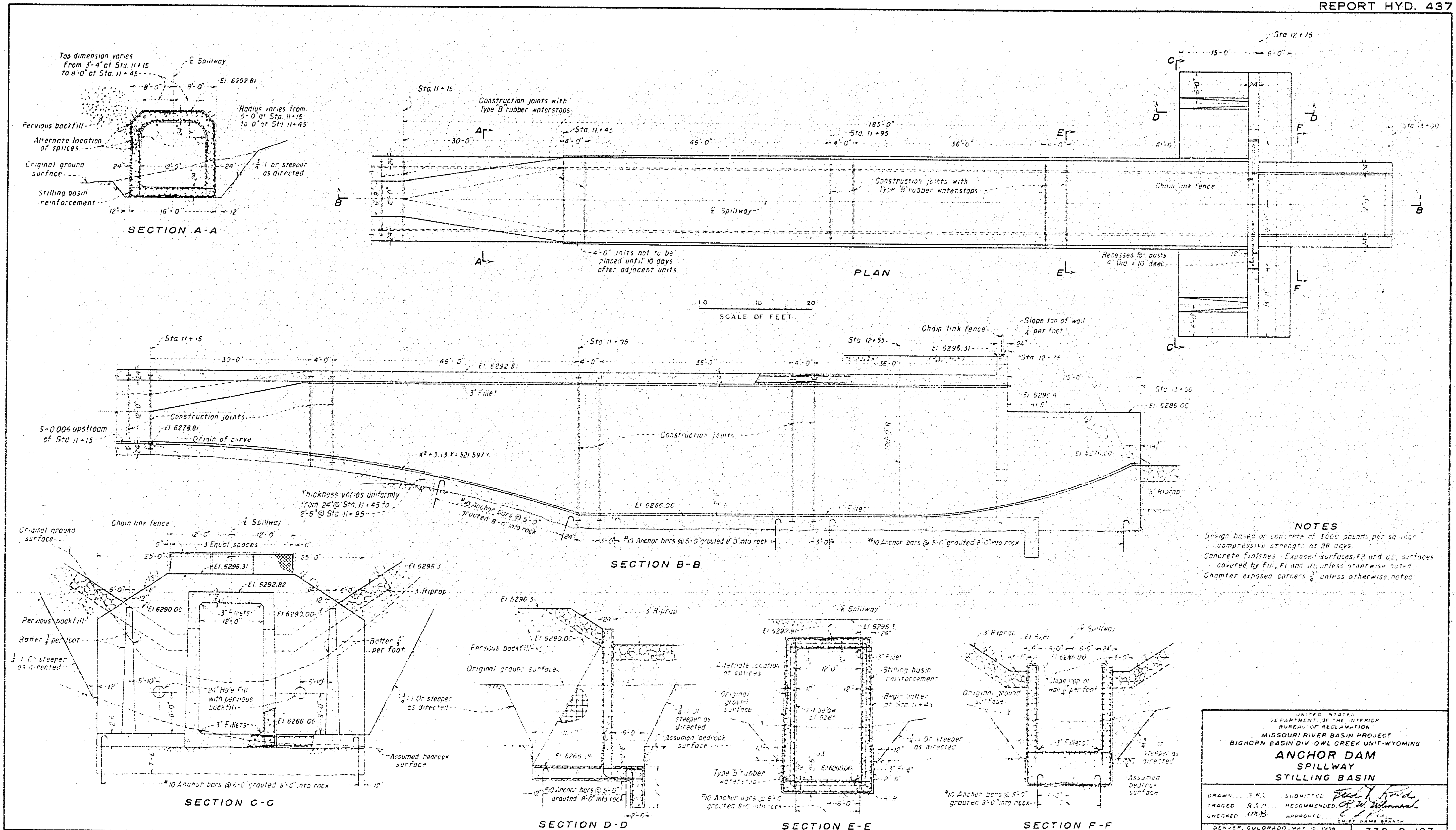
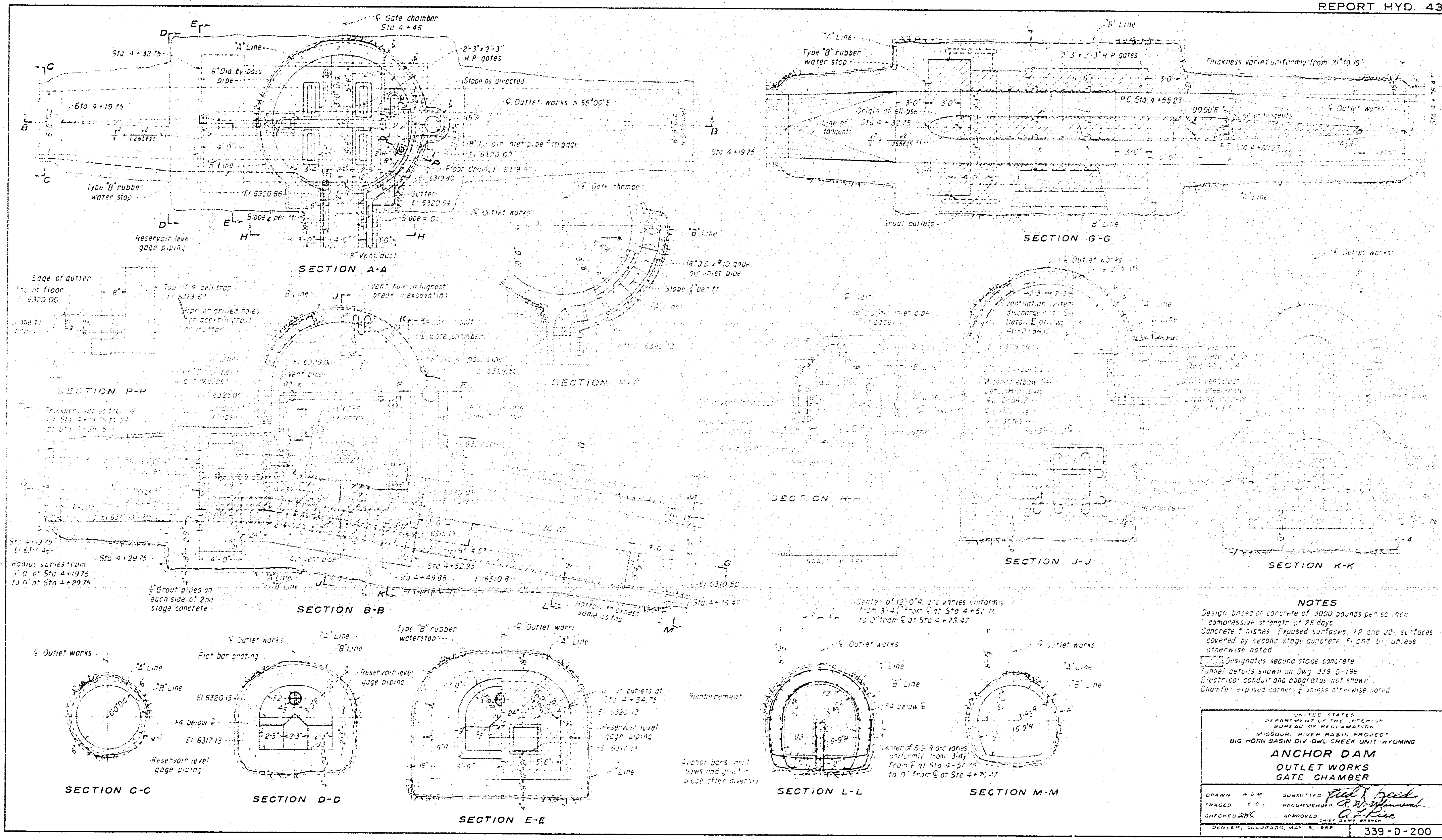
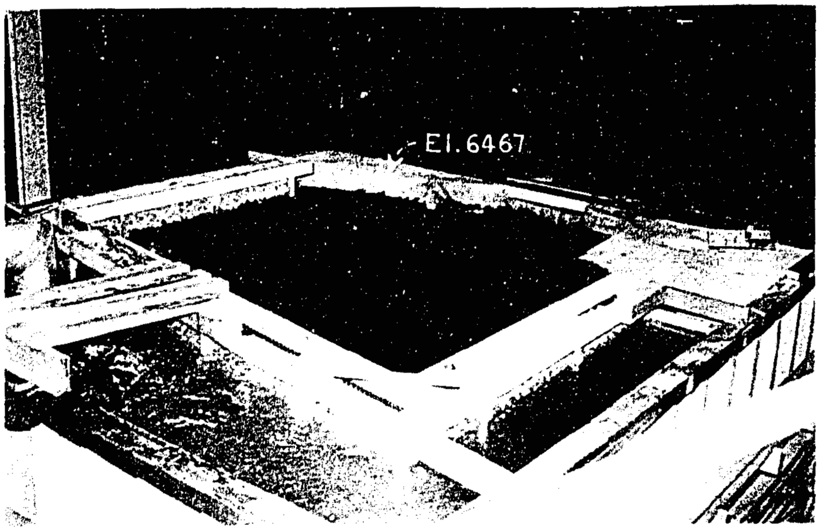

SECTION A-A
PLAN
SCALE OF FEET
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
SECTION F-F
Construction joints with Type "B" rubber waterstops
4'-0" Units not to be placed until 10 days after adjacent units.
Chain link fence
Recesses for posts 4" Dia. x 10" deep
Thickness varies uniformly from 24" @ Sta. 11+45 to 2'-6" @ Sta. 11+95
$X^2 + 3.13X = 521.597Y$
S=0.006 upstream of Sta. 11+15
#10 Anchor bars @ 5'-0" grouted 8'-0" into rock
NOTES
Design based on concrete of 3000 pounds per sq. inch compressive strength at 28 days.
Concrete finishes: Exposed surfaces, F2 and U2; surfaces covered by fill, F1 and U1, unless otherwise noted.
Chamfer exposed corners 3/4" unless otherwise noted.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
BIGHORN BASIN DIV.-OWL CREEK UNIT-WYOMING
ANCHOR DAM
SPILLWAY
STILLING BASIN
DENVER, COLORADO, MAY 15, 1956
339-D-197

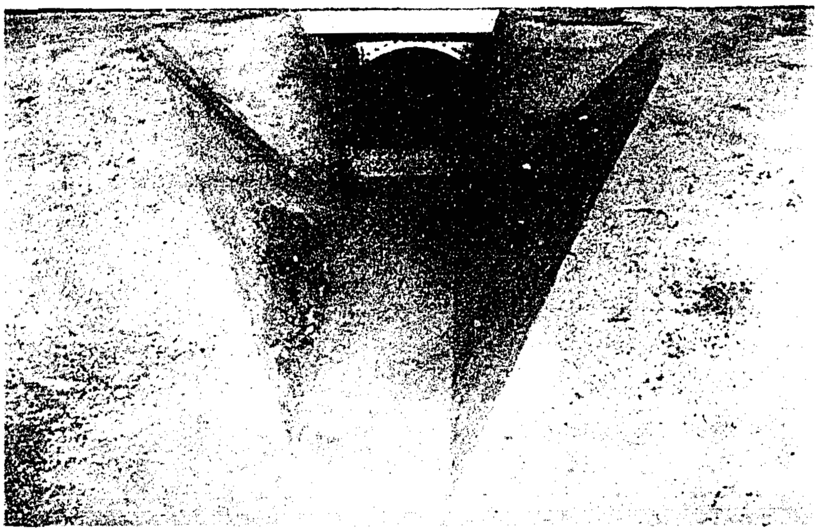
FIGURE 7
REPORT HYD. 437



ANCHOR DAM SPILLWAY AND OUTLET WORKS
1:15.8 Scale Model

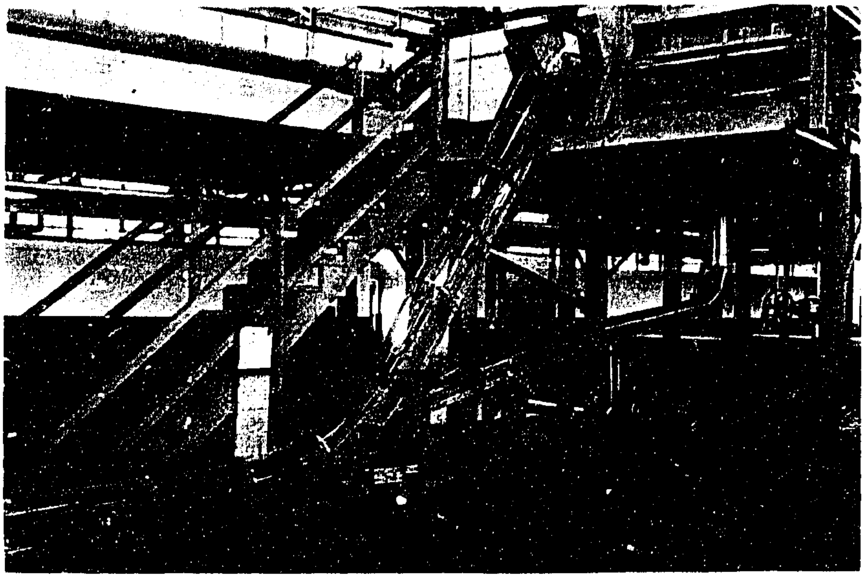


a. Reservoir area

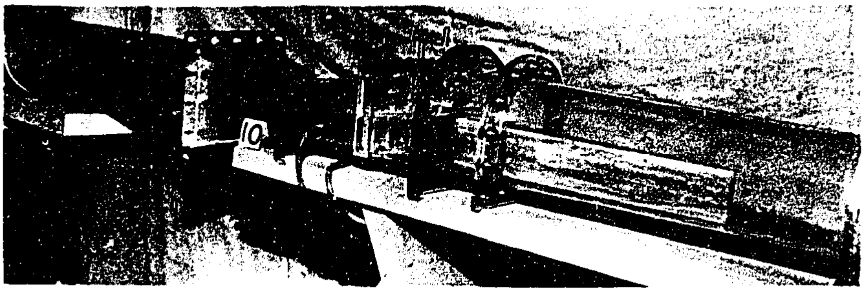


b. Approach channel and crest

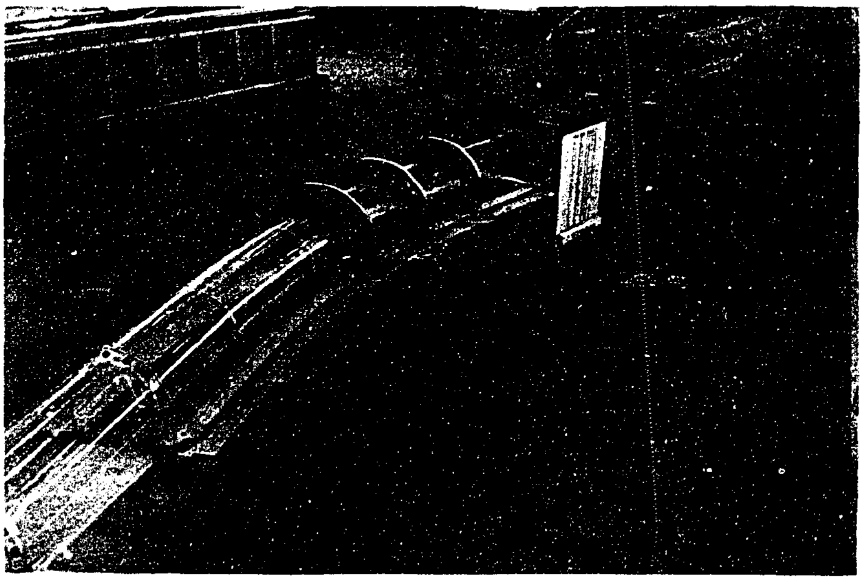
ANCHOR DAM SPILLWAY
Model Reservoir and Spillway Approach
1:15.8 Scale Model



a.
Spillway & outlet works tunnels

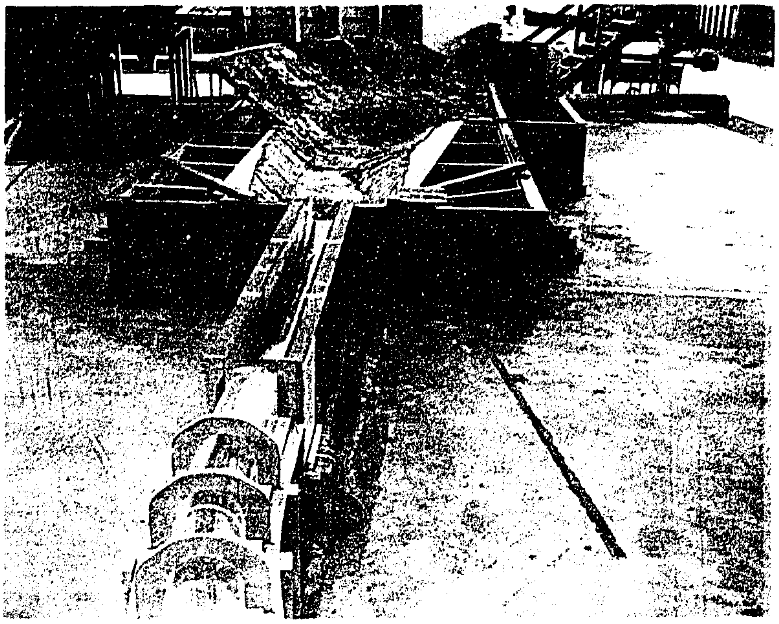


b.
Outlet works control gates

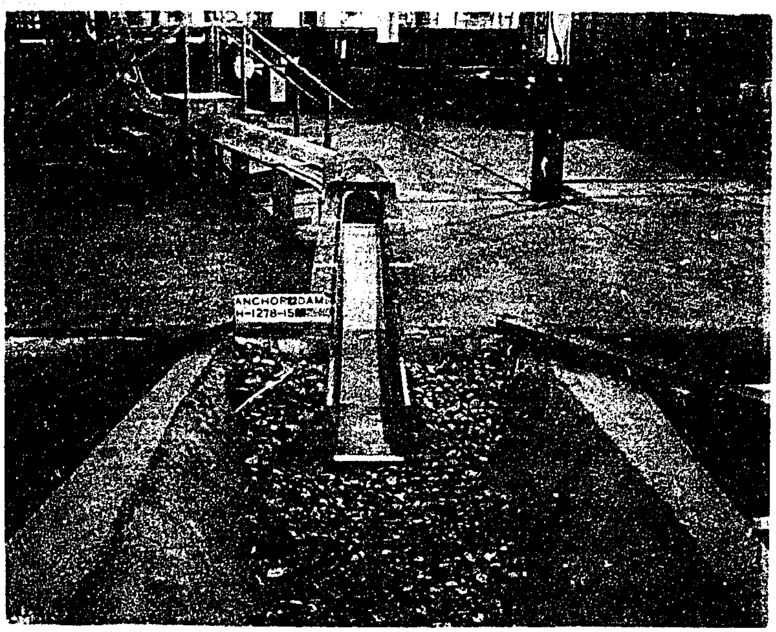


c.
Horizontal bend in spillway tunnel

ANCHOR DAM SPILLWAY AND OUTLET WORKS
Model Tunnels
1:15.8 Scale Model

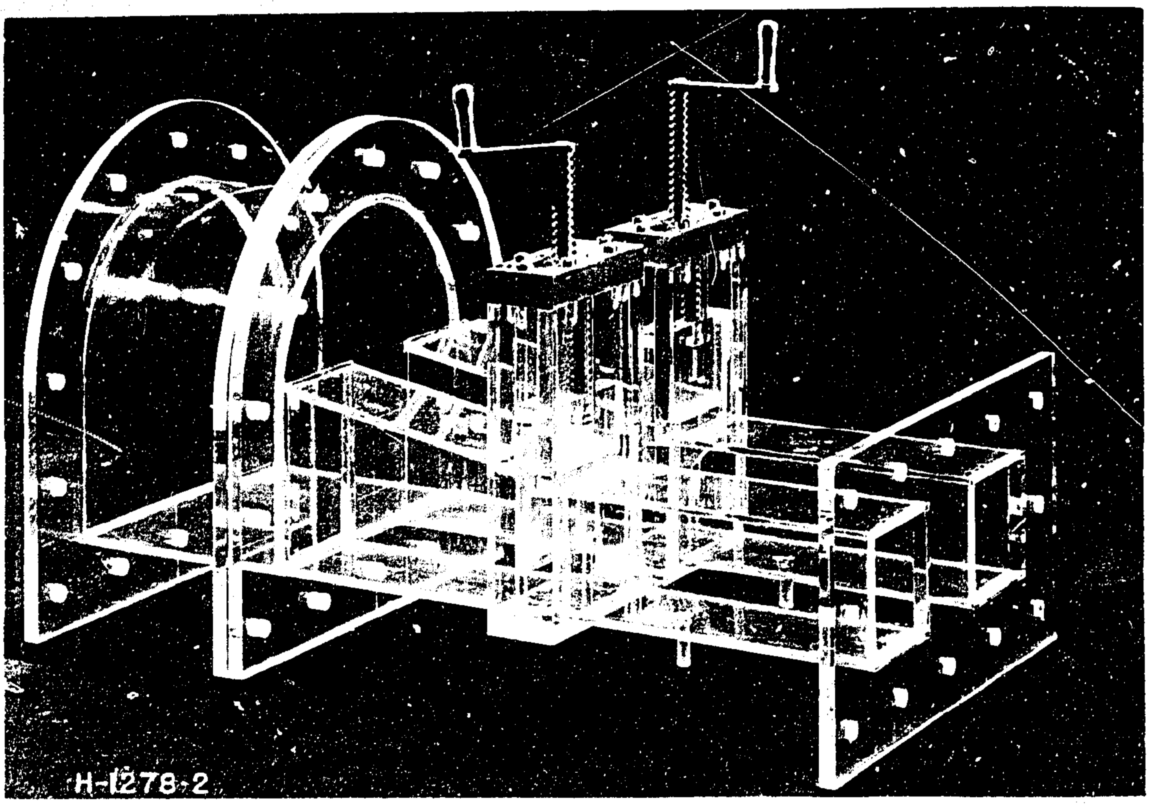


a. Looking downstream at stilling basin and river channel.



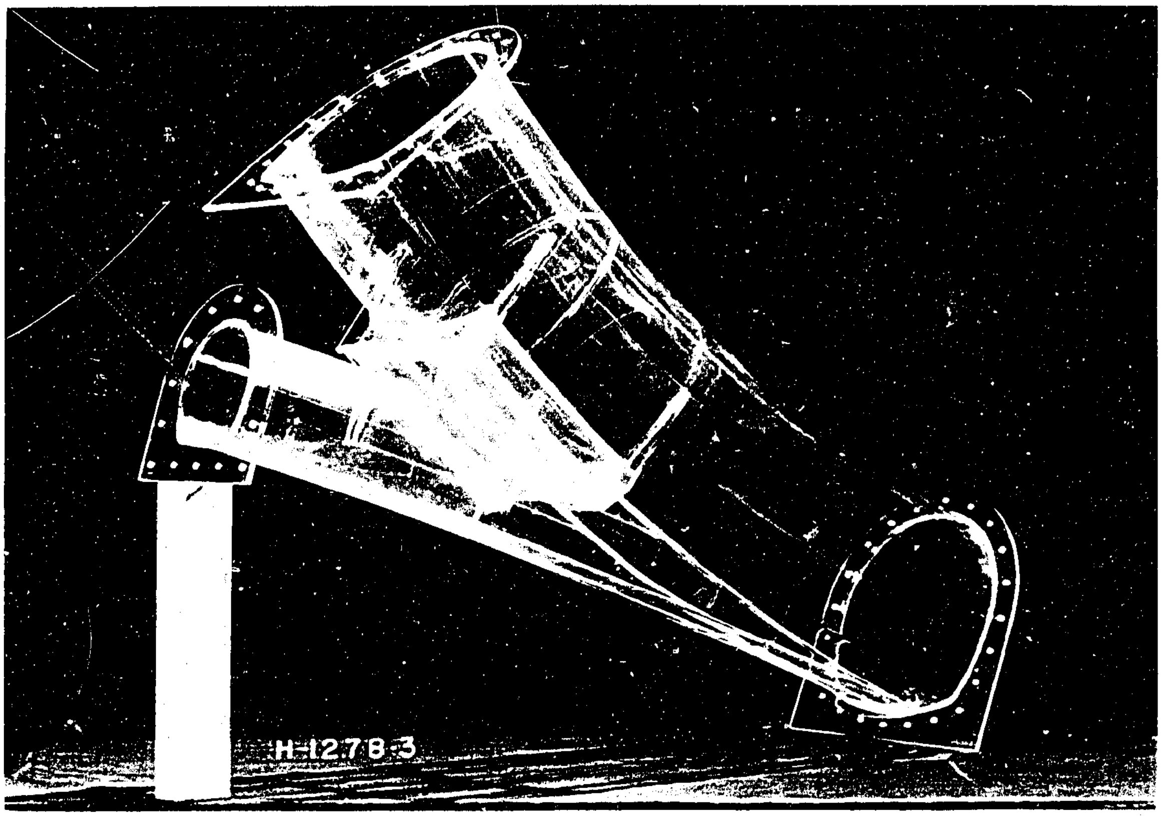
b. Model riprap at end of stilling basin, $1\frac{1}{2}$ to $2\frac{1}{4}$ inches.

ANCHOR DAM SPILLWAY
Model Basin and River Channel
1:15.8 Scale Model



Gates are 1.71 inches square.

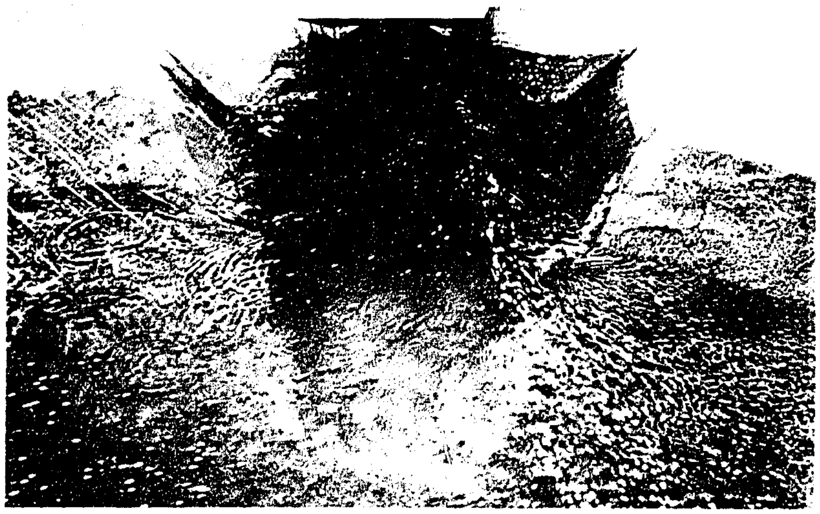
ANCHOR DAM OUTLET WORKS
Model Gate Structure
1:15.8 Scale Model



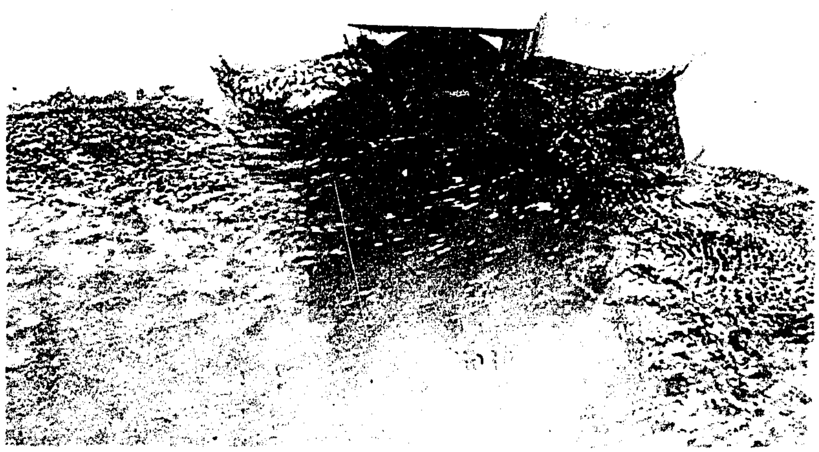
Spillway tunnel diameter 9.1 inches
Outlet tunnel diameter 4.56 inches
Spillway bend radius 71.2 inches on invert

ANCHOR DAM SPILLWAY AND OUTLET WORKS
Model Outlet Works and Spillway
Tunnel Junction
1:15.8 Scale Model

a. 1,100 second-feet



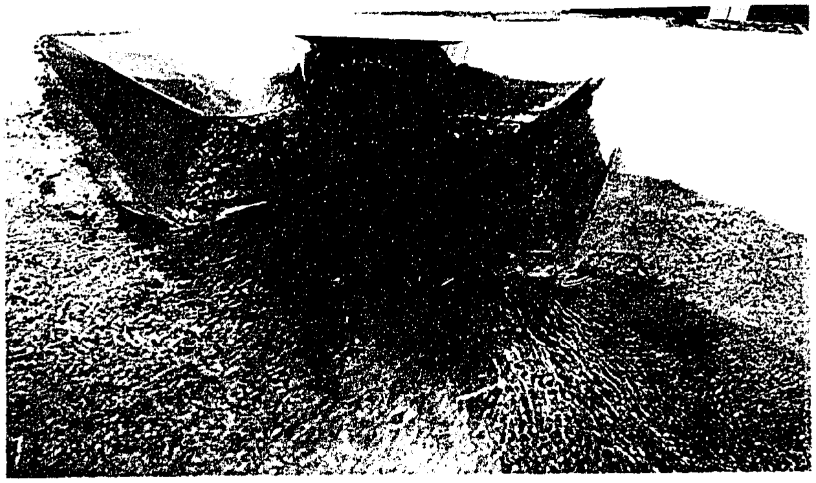
b. 4,000 second-feet



c.
7,150 second-feet

ANCHOR DAM SPILLWAY
Flow in Recommended Approach Channel
1:15.8 Scale Model

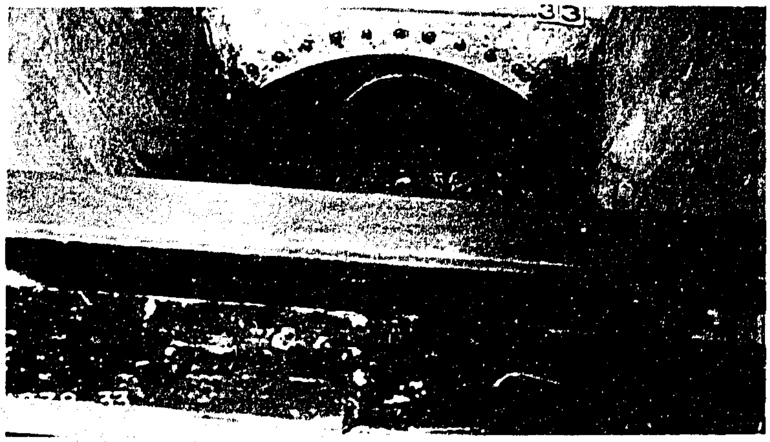
a.
Dark concrete on left is modified approach area.



b.
4,000 second-feet

c.
7,150 second-feet

ANCHOR DAM SPILLWAY
Flow in Preliminary Approach Channel
1:15.8 Scale Model

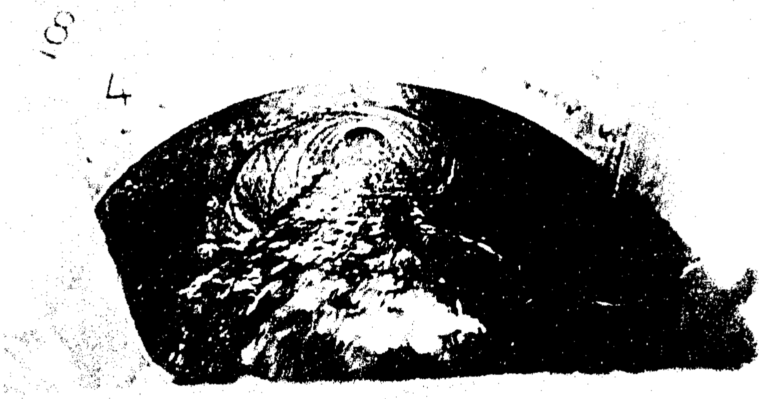


a.
4,000 second-feet.
Looking into tunnel entrance.

b.
7,150 second-feet.
Looking into tunnel entrance.

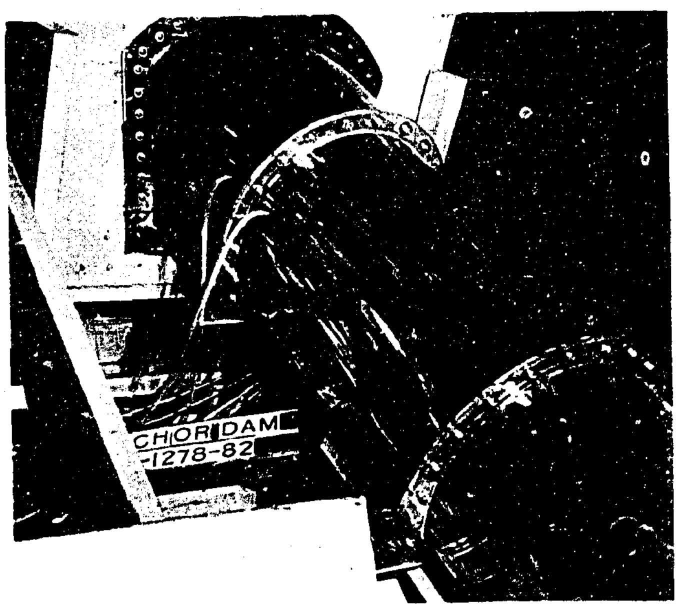
c.
7,150 second-feet.
Looking into side of tunnel entrance.

ANCHOR DAM SPILLWAY
Flow in Tunnel Entrance--Preliminary Approach Channel
1:15.8 Scale Model



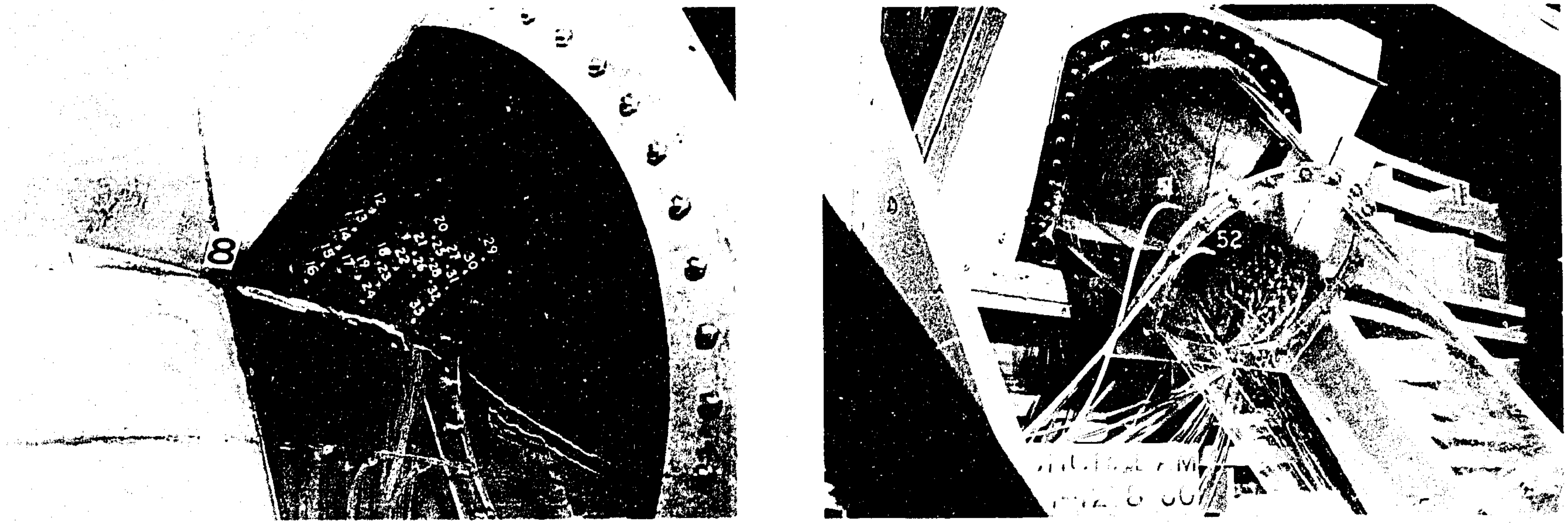
a.
4,000 second-feet.
Looking into tunnel entrance.

b.
7,150 second-feet.
Looking into tunnel entrance.



c.
7,150 second-feet.
Looking into side of tunnel entrance.

ANCHOR DAM SPILLWAY
Flow in Tunnel Entrance--Recommended Approach Channel
1:15.8 Scale Model



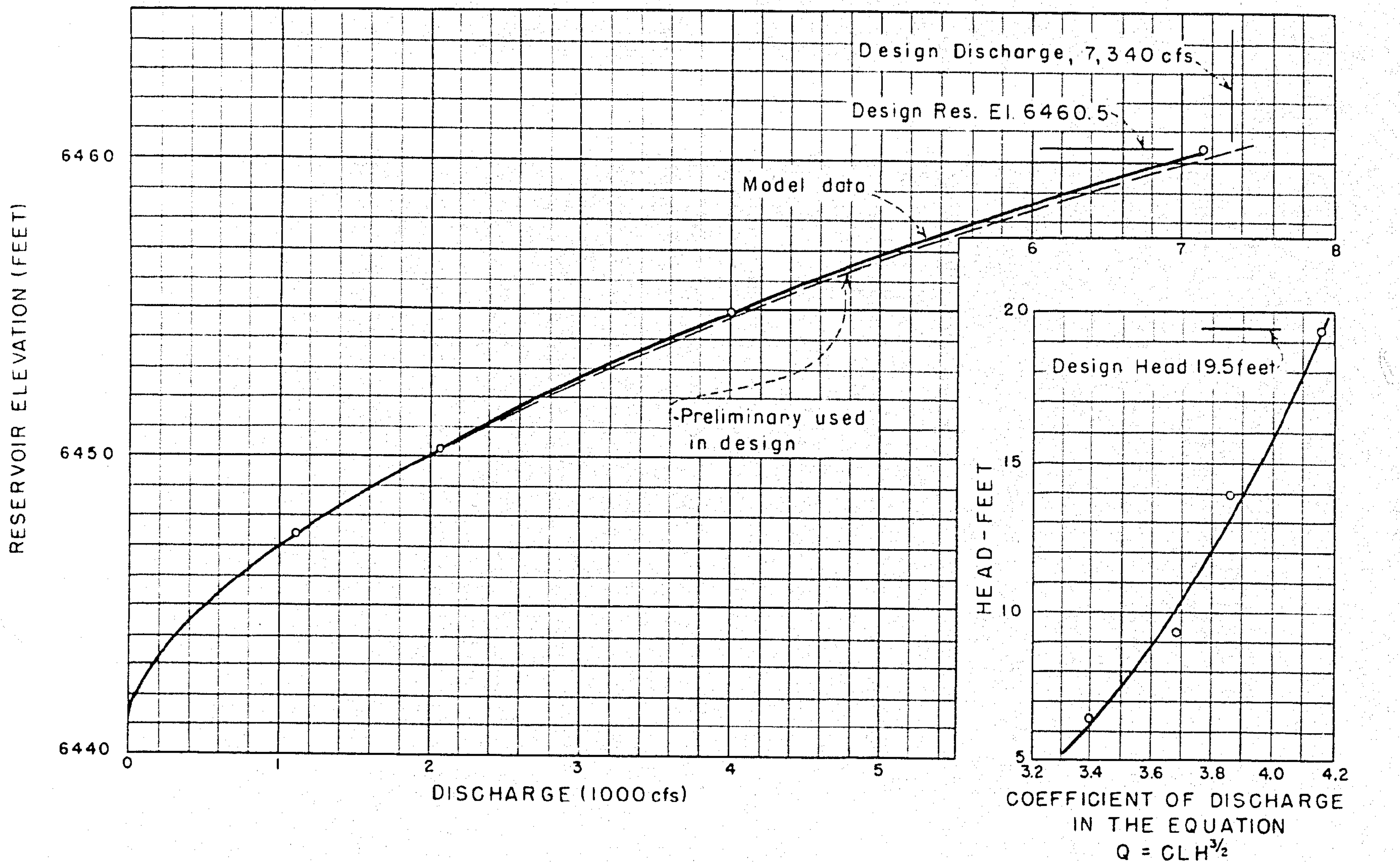
PIEZ. NO.	12	13	14	15	16	17	18	19	20	21	22	23
Q = 1,000 c.f.s. Pressure ft.	0	0	0	0	0	+0.2	-0.1	+0.3	0	0	0	+0.1
Q = 7,134 c.f.s. Pressure ft.	+0.6	+0.8	+1.5	+1.9	+3.4	+2.8	+1.5	+3.1	+0.6	+1.2	+1.2	+2.9

PIEZ. NO.	24	25	26	27	28	29	30	31	32	33	51	52
Q = 1,000 c.f.s. Pressure ft.	+1.3	0	0	0	0	0	0	0	+0.1	+0.7		
Q = 7,134 c.f.s. Pressure ft.	+4.0	+1.0	+2.4	+1.5	+2.3	+0.5	+1.4	+2.1	+2.6	+2.9		
Q = 7,200 c.f.s. Pressure ft.											-0.3	-0.7

Pressure in feet of water. NOTE: Zero pressure is atmospheric pressure.

ANCHOR DAM SPILLWAY
Pressures In Upstream Tunnel Transition
1:15.8 Scale Model

Figure 18
Report Hyd. 437

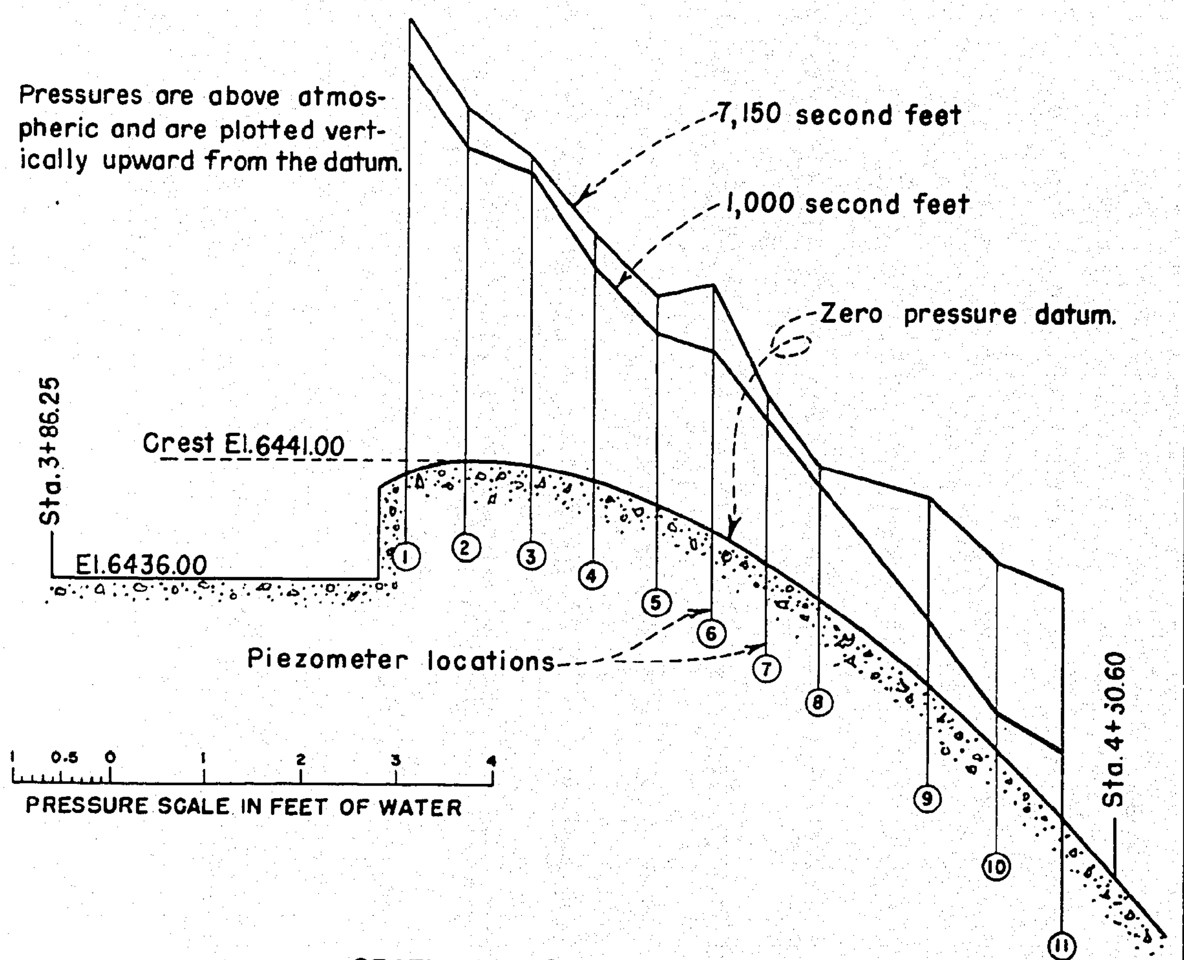


ANCHOR DAM SPILLWAY

SPILLWAY CAPACITY CURVES

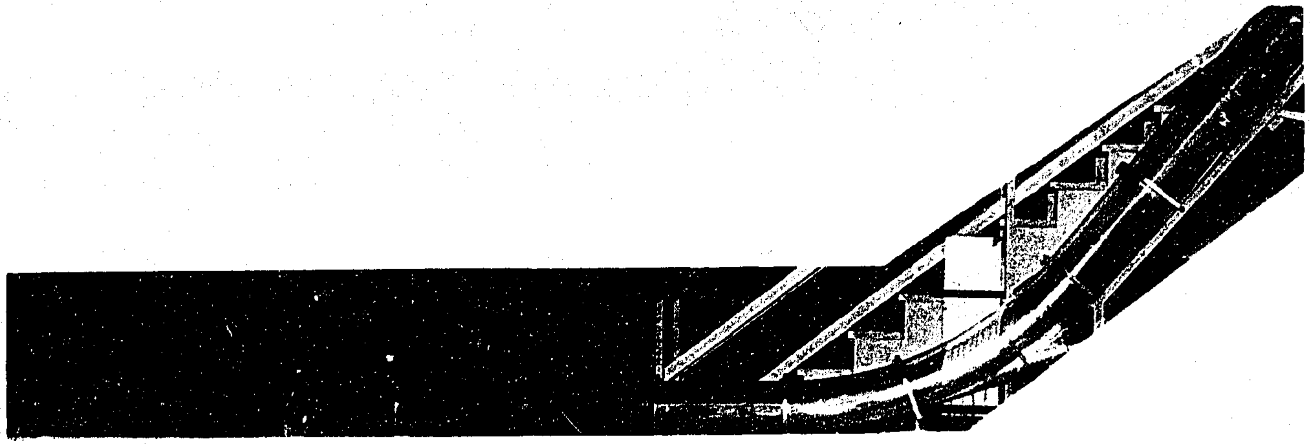
1:15.8 SCALE MODEL

FIGURE 19
REPORT HYD. 437

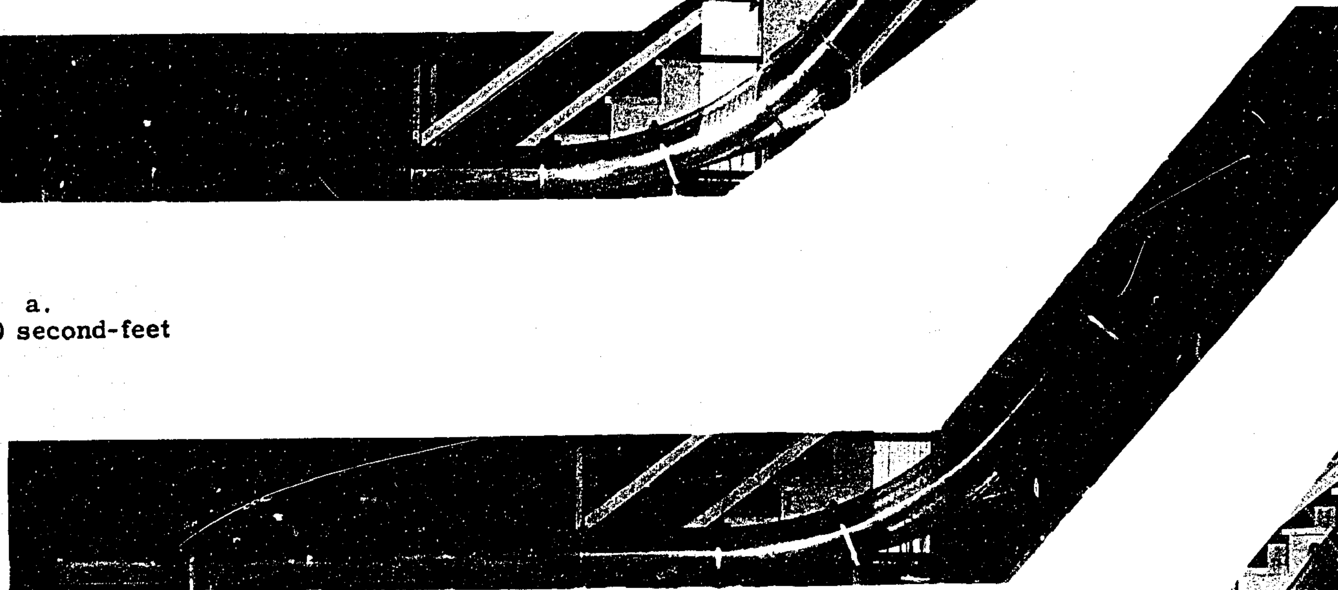


SECTION ON ℄ OF SPILLWAY

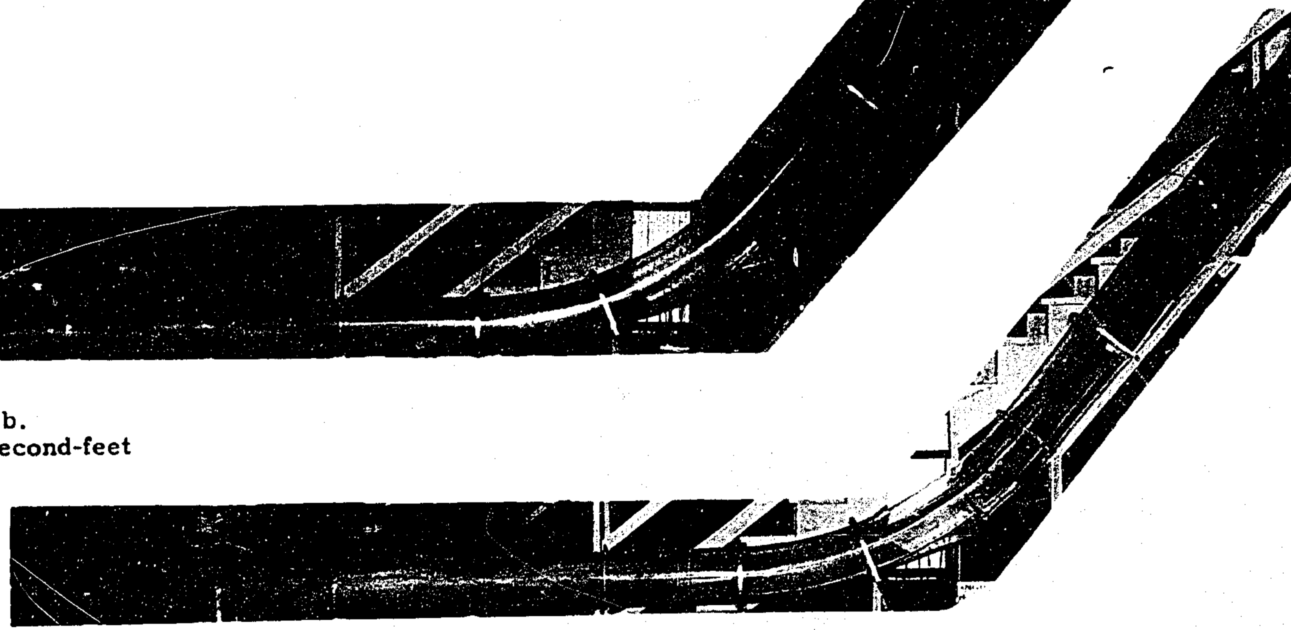
ANCHOR DAM SPILLWAY
CREST PRESSURES
1:15.8 SCALE MODEL



a.
1,100 second-feet

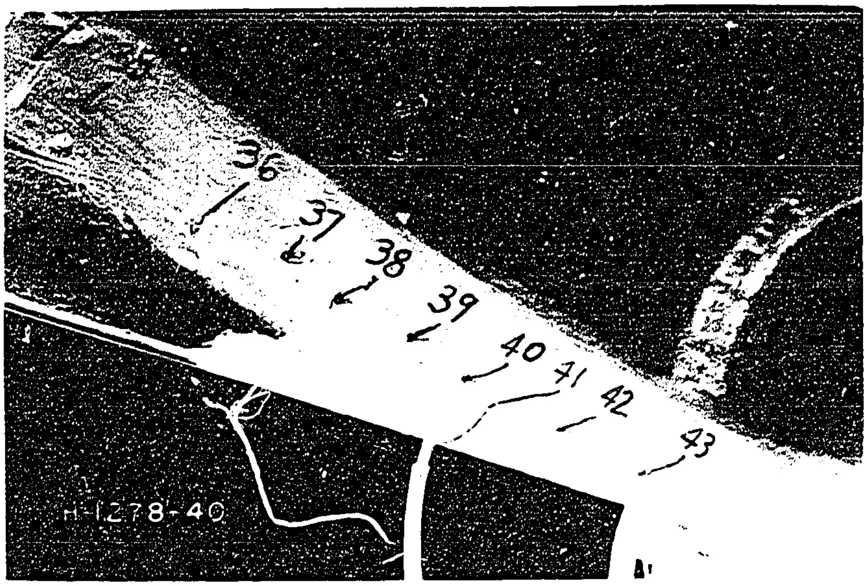


b.
4,000 second-feet

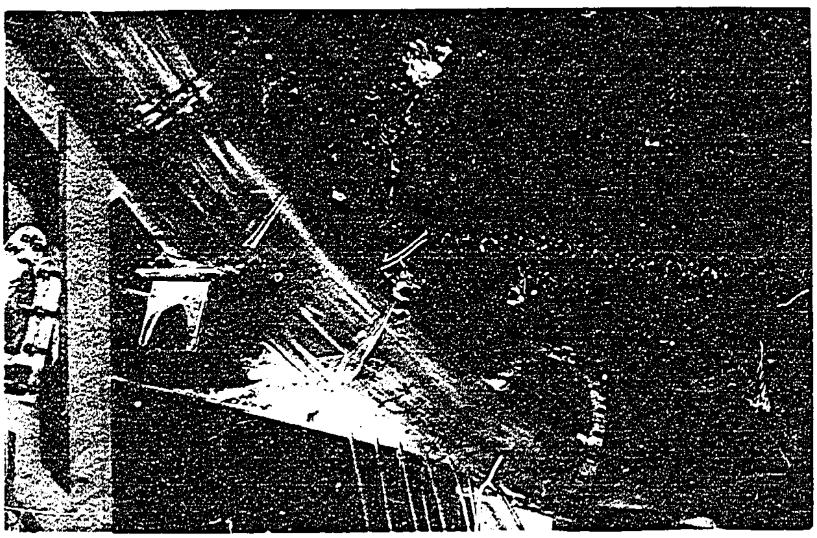


c. 7,150 second-feet

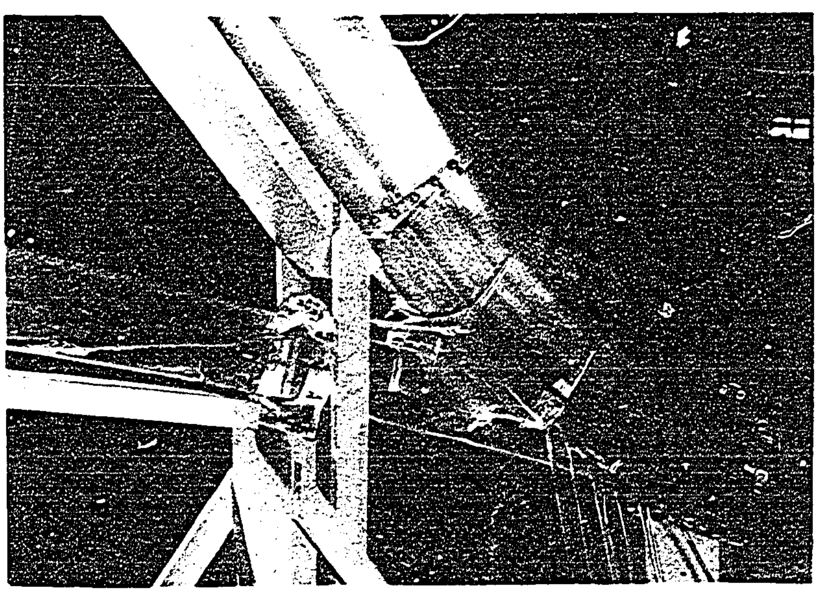
ANCHOR DAM SPILLWAY
Flow in the Spillway Tunnel
1:15.8 Scale Model



a.
1,100 second-feet

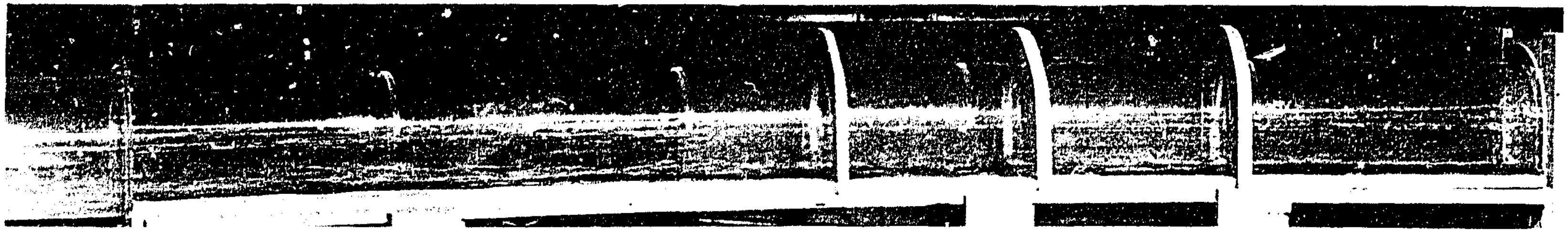


b.
4,000 second-feet

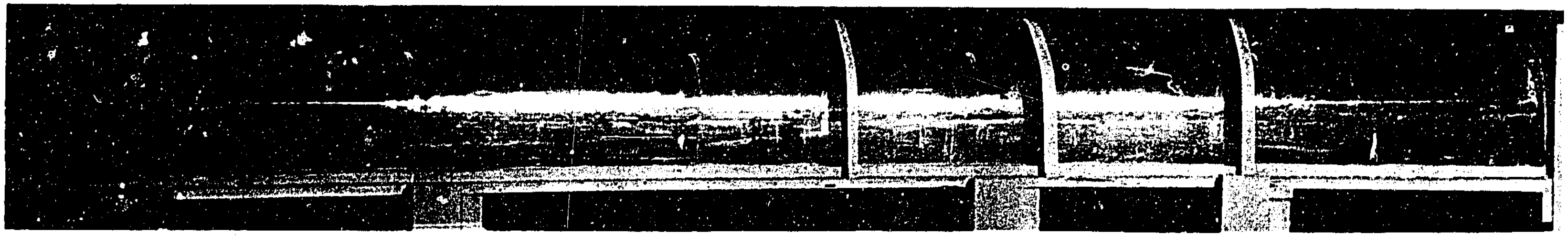


c.
7,150 second-feet

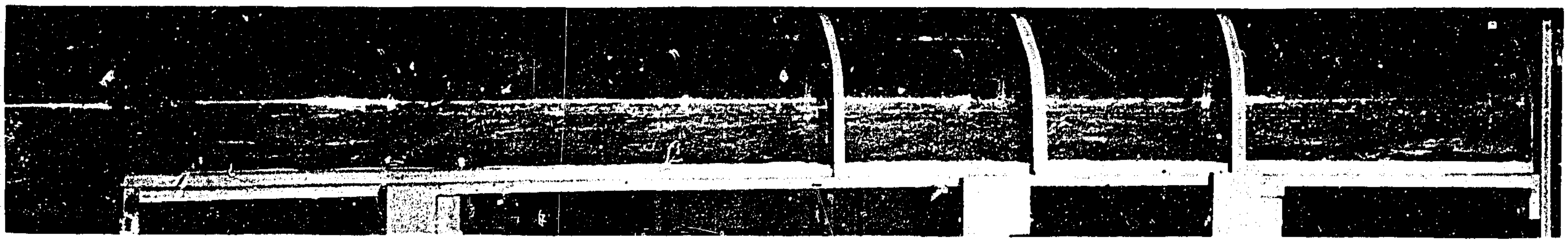
ANCHOR DAM SPILLWAY
Flow through the Vertical Bend
1:15.8 Scale Model



a. 300 second-feet



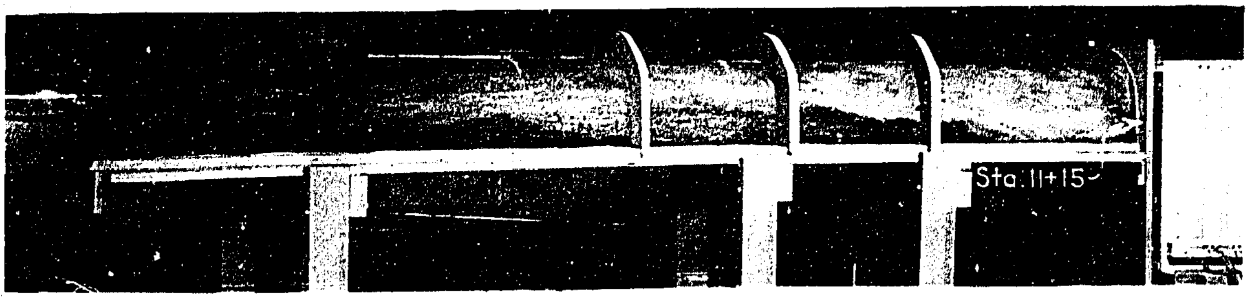
b. 640 second-feet



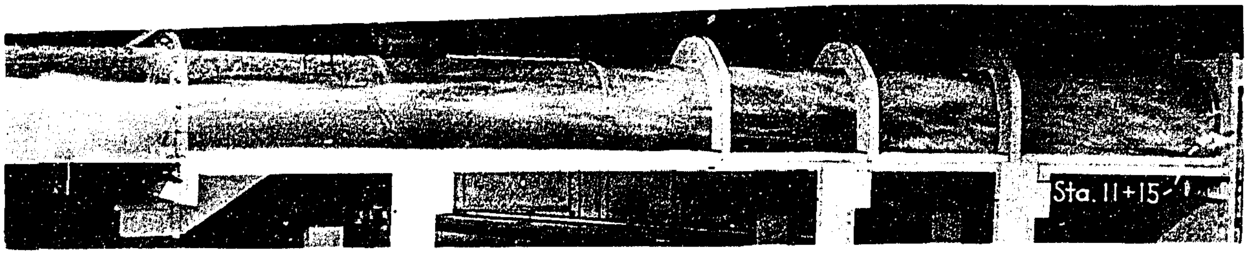
c. 1,100 second-feet

ANCHOR DAM SPILLWAY
Flow through the Horizontal Bend
Small Discharges
1:15.8 Scale Model

Figure 23
Report Hyd-437

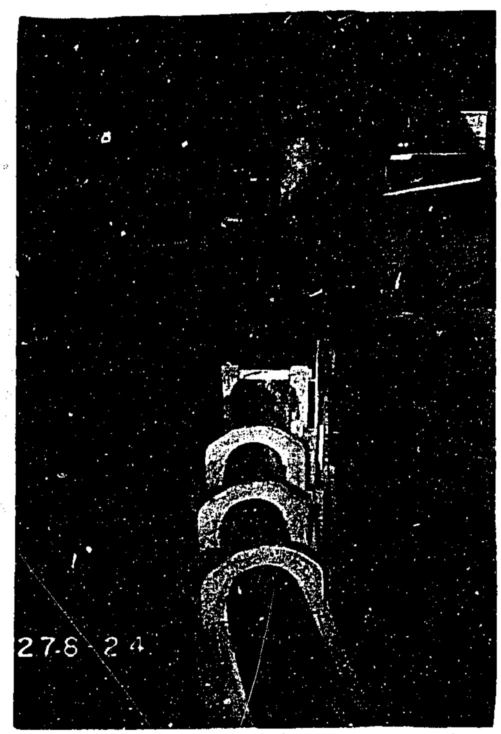


a. 4,000 second-feet. Tunnel partially filled with spray at Station 11+15.



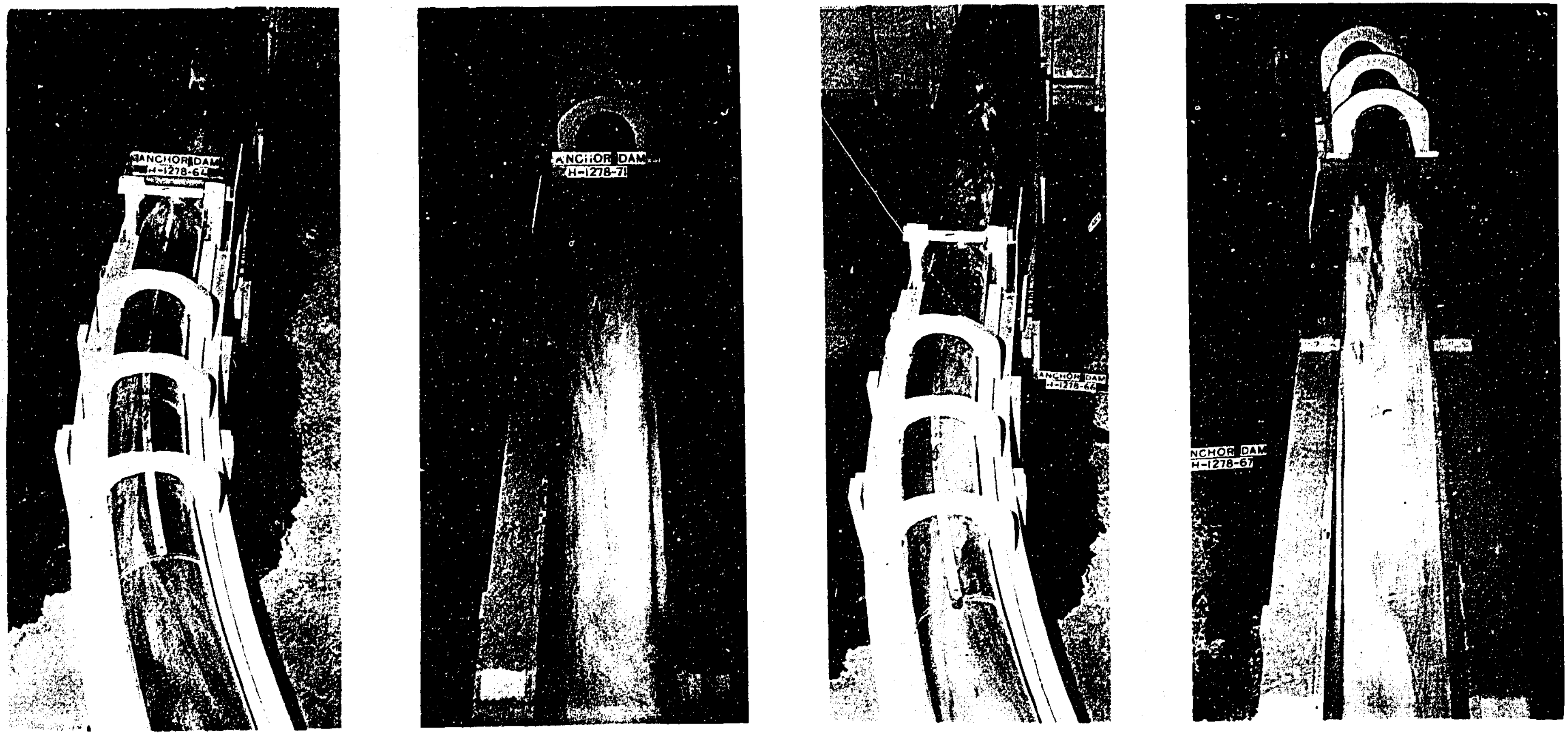
b. 7,150 second-feet. Tunnel filled with spray at Station 11+15.

c. 4,000 second-feet



d. 7,150 second-feet

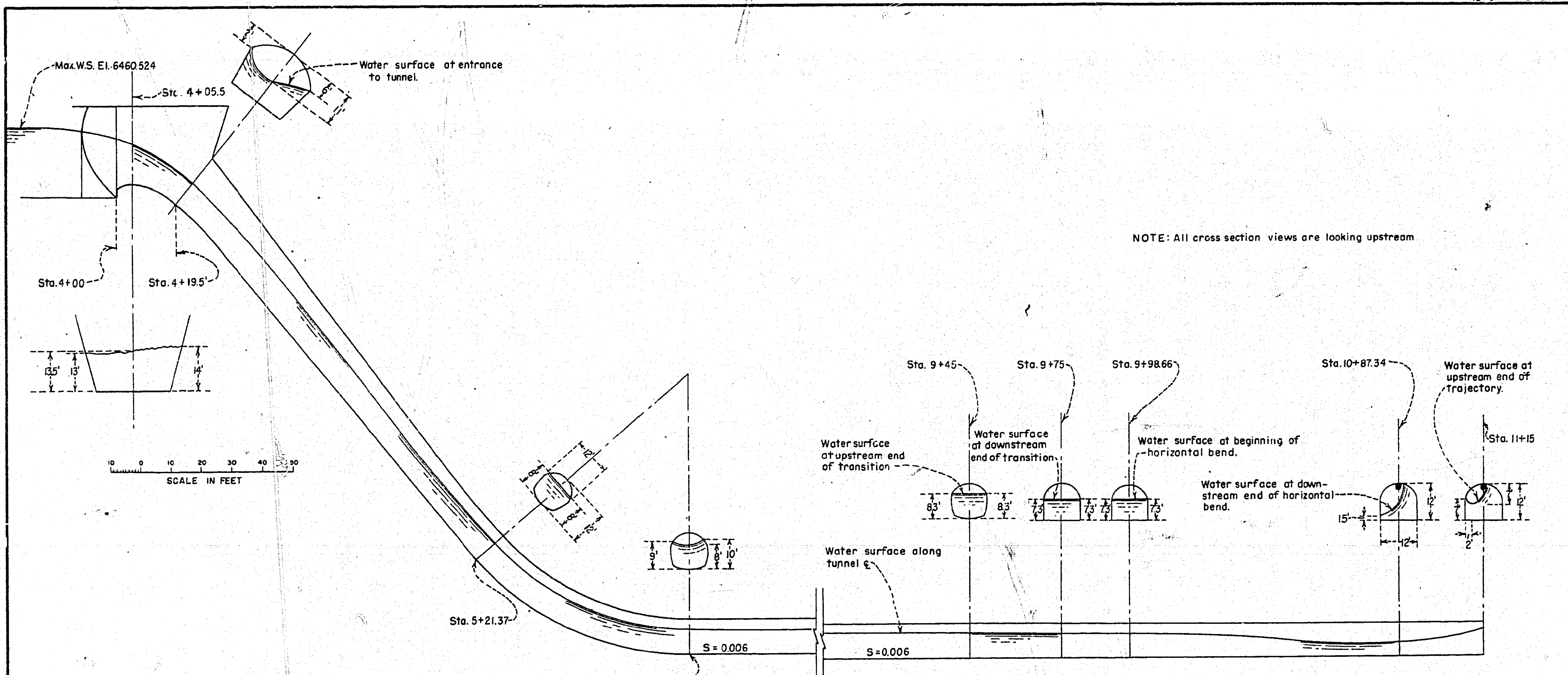
ANCHOR DAM SPILLWAY
Flow through the Horizontal Bend
Large Discharges
1:15.8 Scale Model



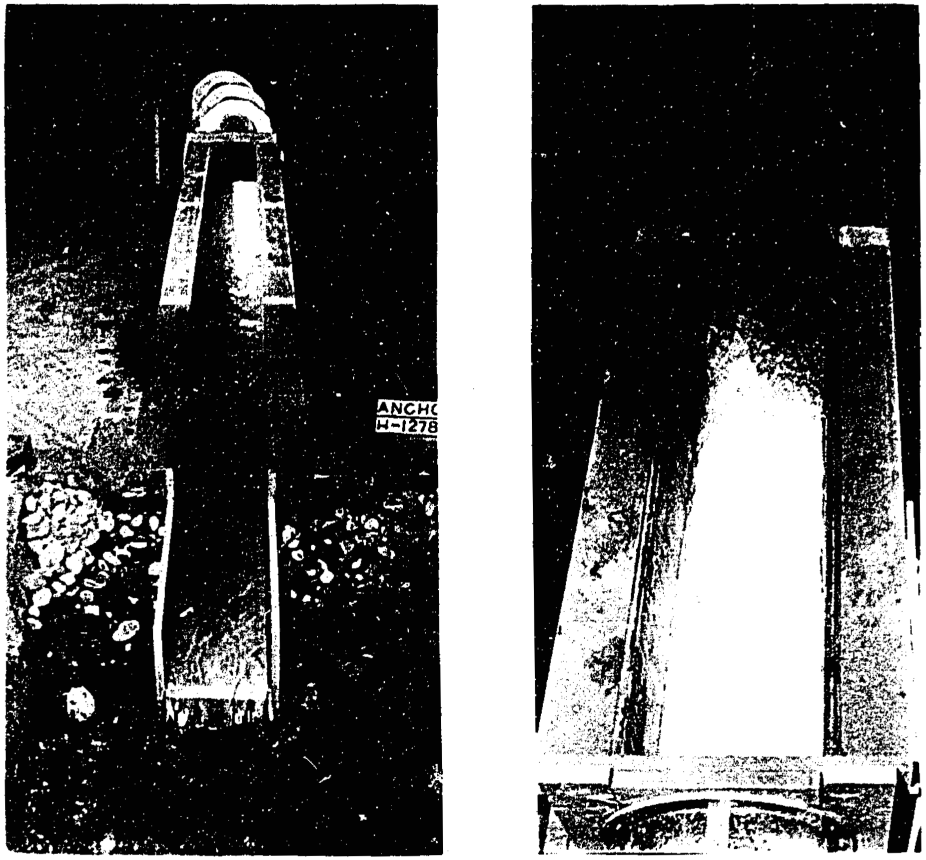
a. 4,000 second-feet b. 3,000 second-feet c. 7,000 second-feet d. 7,000 second-feet

Note: Guide vane on crown of tunnel. See Figure 3 for details. Note the space above the water surface at end of tunnel. See Figure 26 for water surface measure-

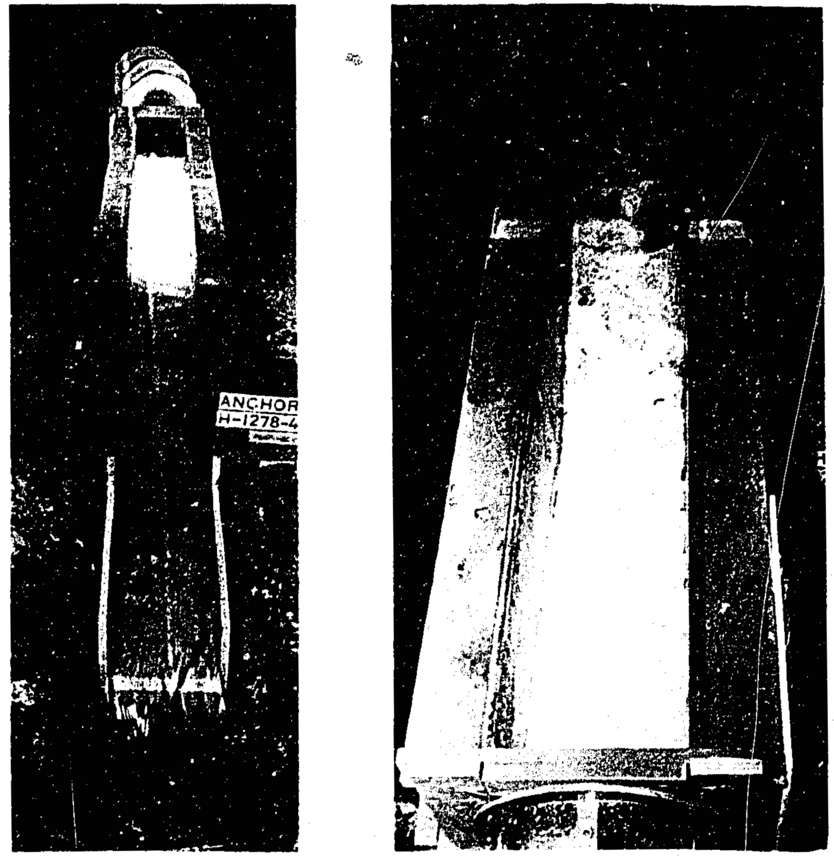
ANCHOR DAM SPILLWAY
Flow through the Horizontal Bend with Recommended Guide Vane
1:15.8 Scale Model



ANCHOR DAM SPILLWAY
TUNNEL WATER SURFACE PROFILE - 7,200 SECOND FEET
1:15.8 SCALE MODEL



a. 300 second-feet



b. 640 second-feet

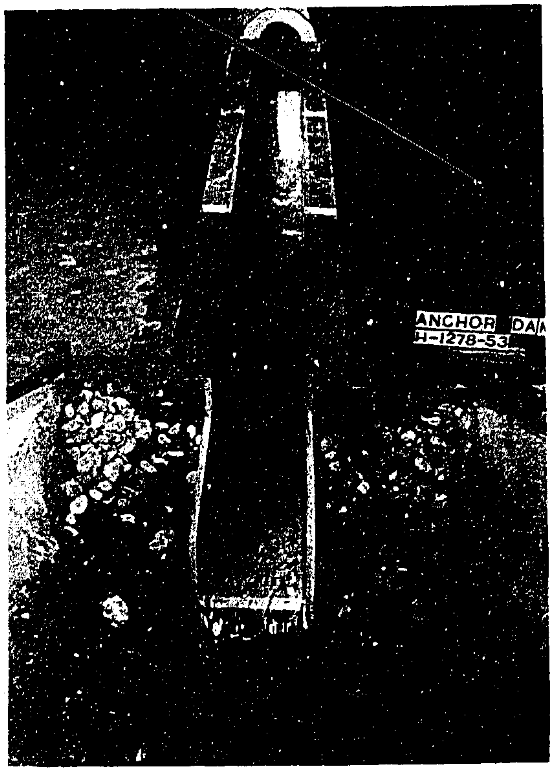
ANCHOR DAM SPILLWAY
Stilling Basin Operating as a Hydraulic Jump Basin
1:15.8 Scale Model

a. Flow in basin

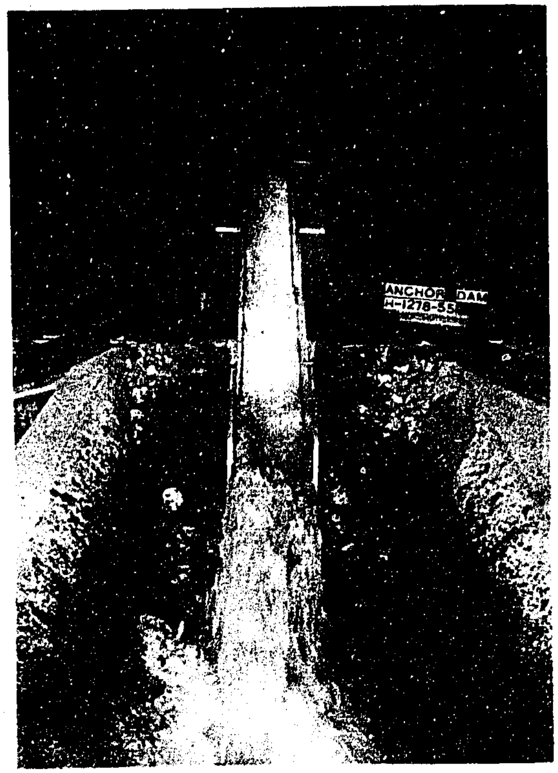
c. Flow at basin entrance

Flow at end of basin

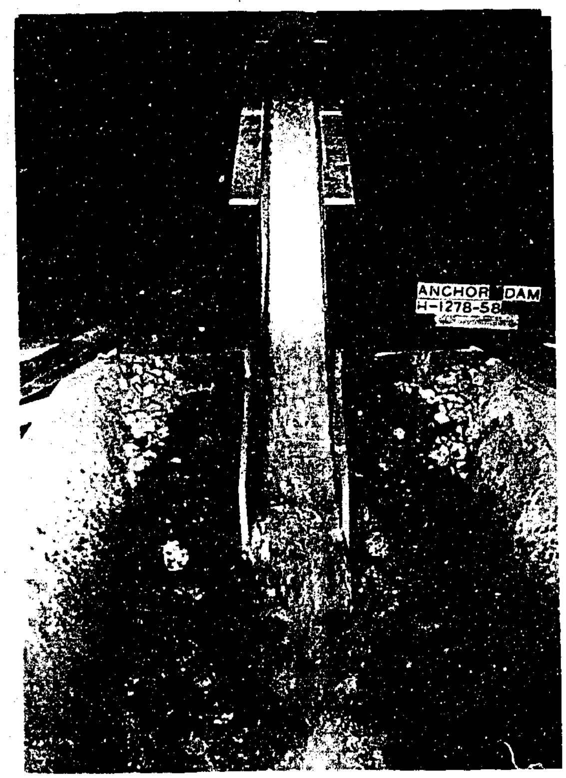
ANCHOR DAM SPILLWAY
Stilling Basin Discharge
1,100 Second-Feet
1:15.8 Scale Model



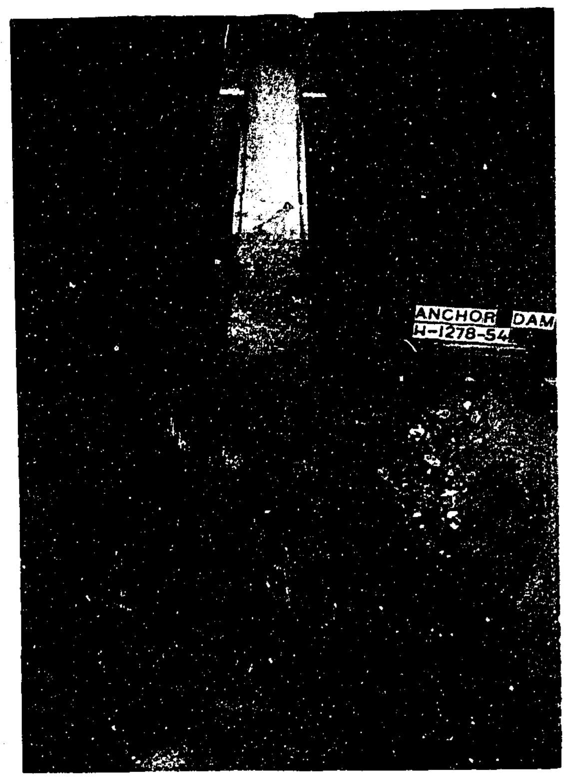
a. 640 second-feet-jump in basin



1,500 second-feet-jump swept from basin

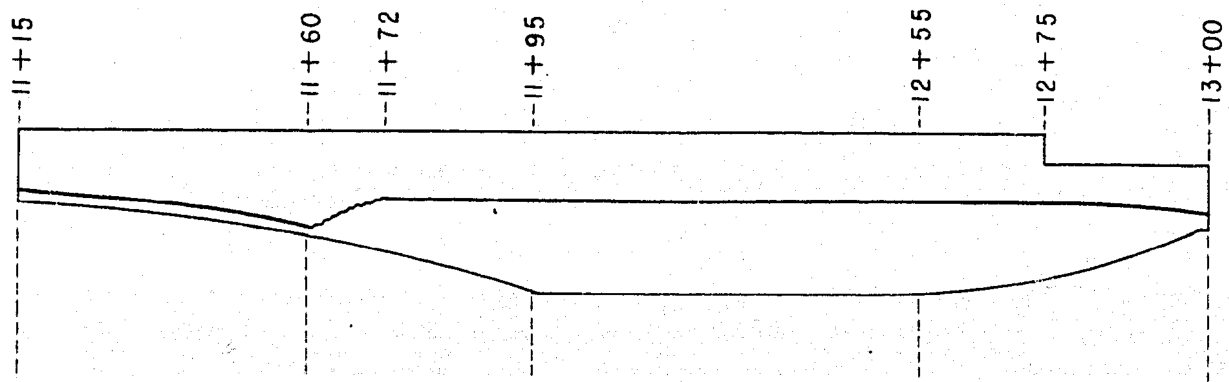


b. The flow has increased from 640 to 1,400 cfs-jump in basin



d. The flow has decreased from 1,500 to 700 cfs-jump has not reformed in basin.

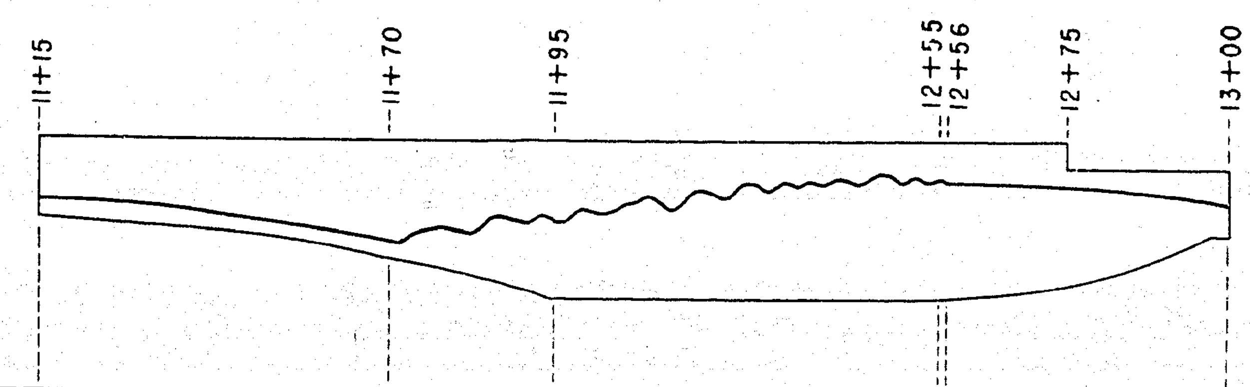
ANCHOR DAM SPILLWAY
Hydraulic Jump Sweepout Tests
1:15.8 Scale Model



	11+15	11+60	12+55	13+00
Left		1.4		
Center	1.4	1.1	14	2.5
Right		1.0		

PROFILE AND DEPTH MEASUREMENTS IN FEET Q = 300 C.F.S.

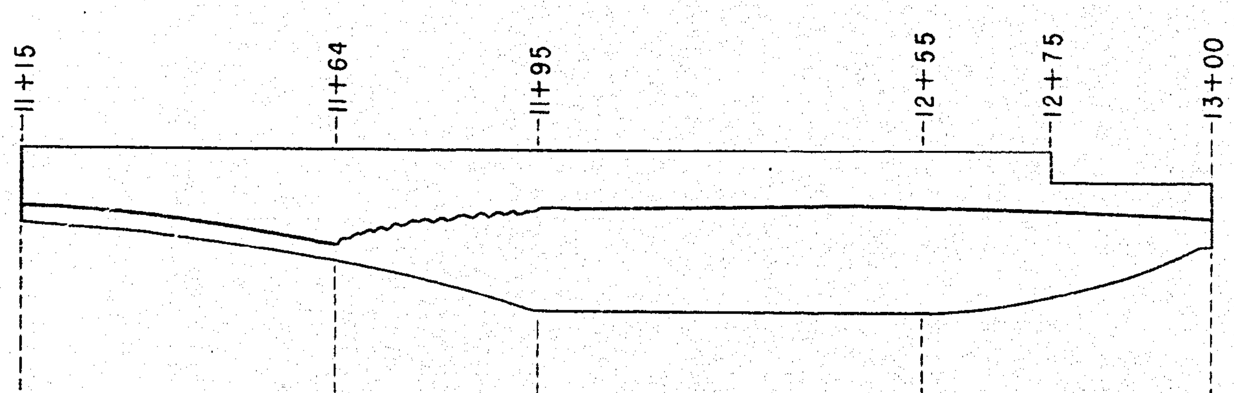
D_1 = 1.1 L = 12' FROUDE NUMBER = 3.81



	11+15	11+70	12+55	13+00
Left	2.5	1		
Center		2.75	18	5.5
Right	4	3.2		

PROFILE AND DEPTH MEASUREMENTS IN FEET Q = 1,000 C.F.S.

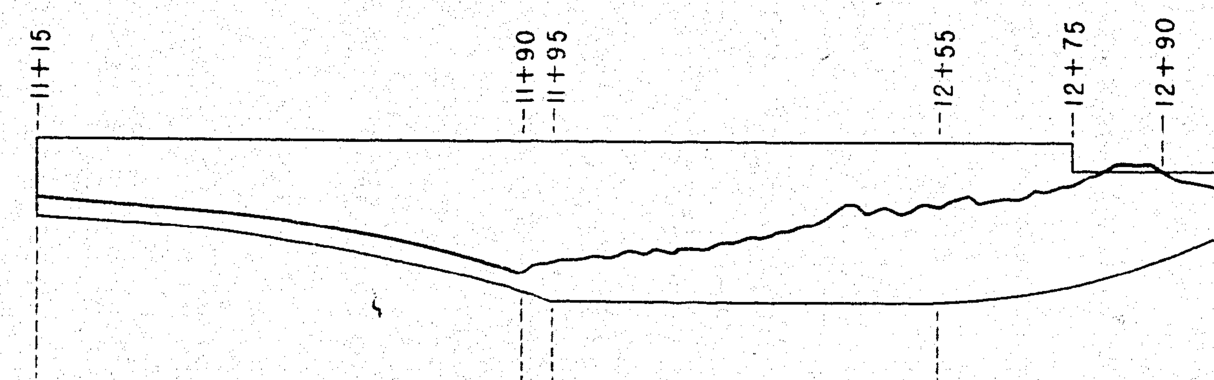
D_1 = 2.75 L = 86' FROUDE NUMBER = 3.26



	11+15	11+64	12+55	13+00
Left	1.5	1.5		
Center		1.75	16	4
Right	.3	2.00		

PROFILE AND DEPTH MEASUREMENTS IN FEET Q = 640 C.F.S.

D_1 = 1.75' L = 35' FROUDE NUMBER = 4.07



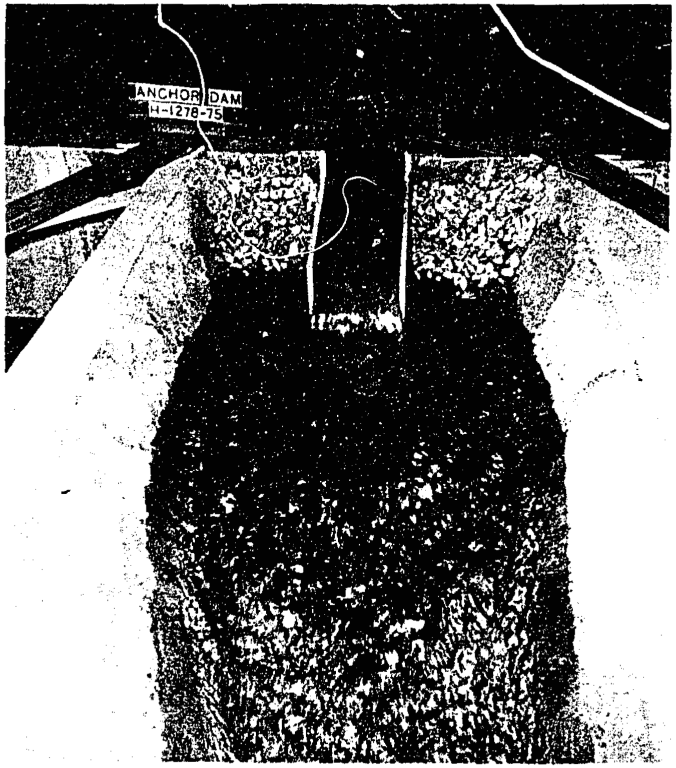
	11+15	11+90	13+00
Left	3.5	1	
Center		3.25	7
Right	4	4	

PROFILE AND DEPTH MEASUREMENTS IN FEET Q = 1,400 C.F.S.

D_1 = 3.25' L = 100' FROUDE NUMBER = 3.58

NOTE: Depths are measured vertically. D_1 is the average measured depth at the toe of the jump. L is the estimated length of the jump based on surface boil. Froude number is computed using D_1.

ANCHOR DAM SPILLWAY
WATER SURFACE IN STILLING BASIN
SMALL DISCHARGES
1:15.8 SCALE MODEL



a. 640 second-feet

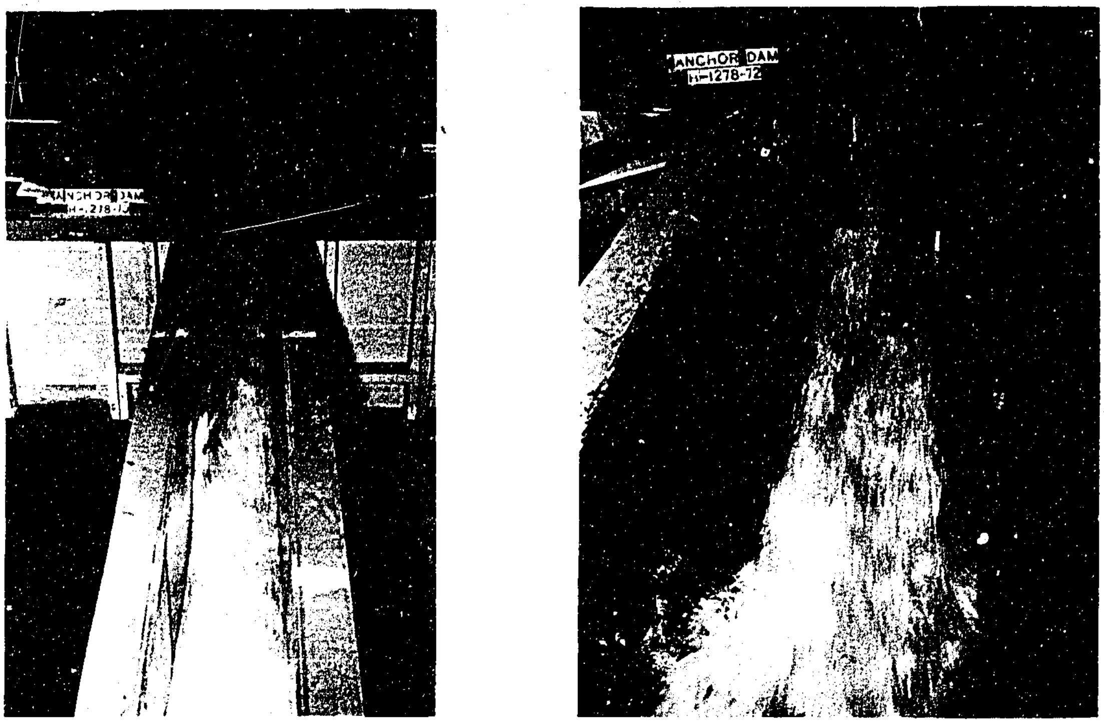
b. Erosion after 20 minute model test.

ANCHOR DAM SPILLWAY
Erosion Test--640 Second-Feet
1:15.8 Scale Model

a. 1,400 second-feet

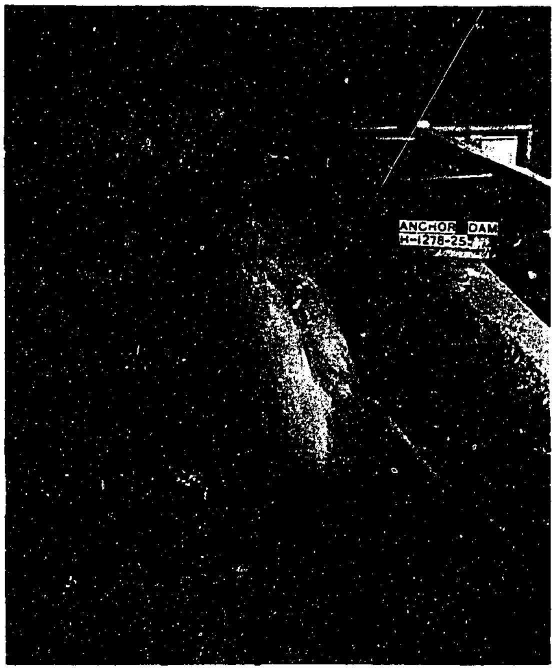
b. Erosion after 20 minute model test at 640 second-feet plus 20 more minutes at 1,400 second-feet.

ANCHOR DAM SPILLWAY
Erosion Test--1,400 Second-Feet
1:15.8 Scale Model



a. 3,000 second-feet

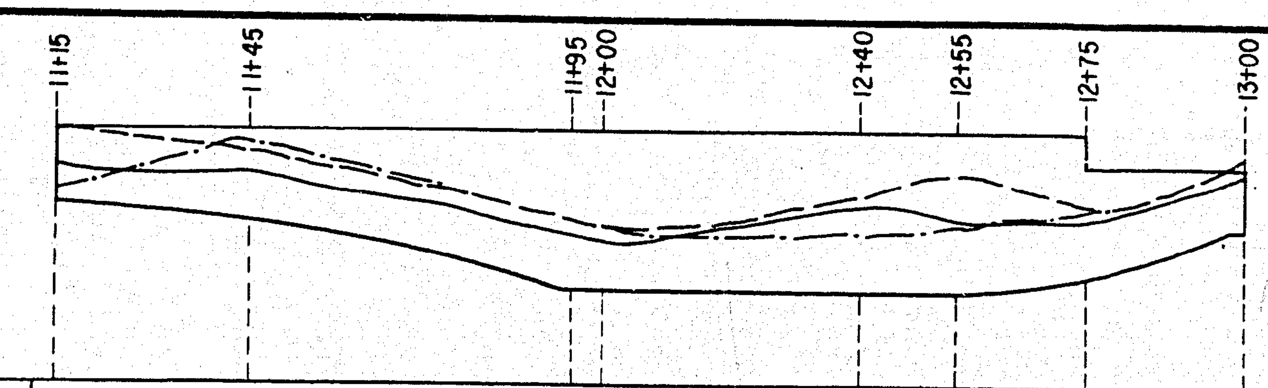
b. 4,000 second-feet



7,150 second-feet

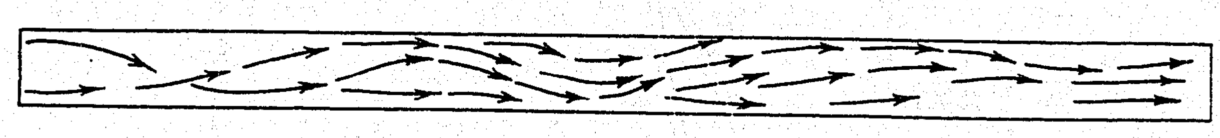
ANCHOR DAM SPILLWAY
Stilling Basin Operating
As a Flip Bucket
1:15.8 Scale Model

FIGURE 34
REPORT HYD 437

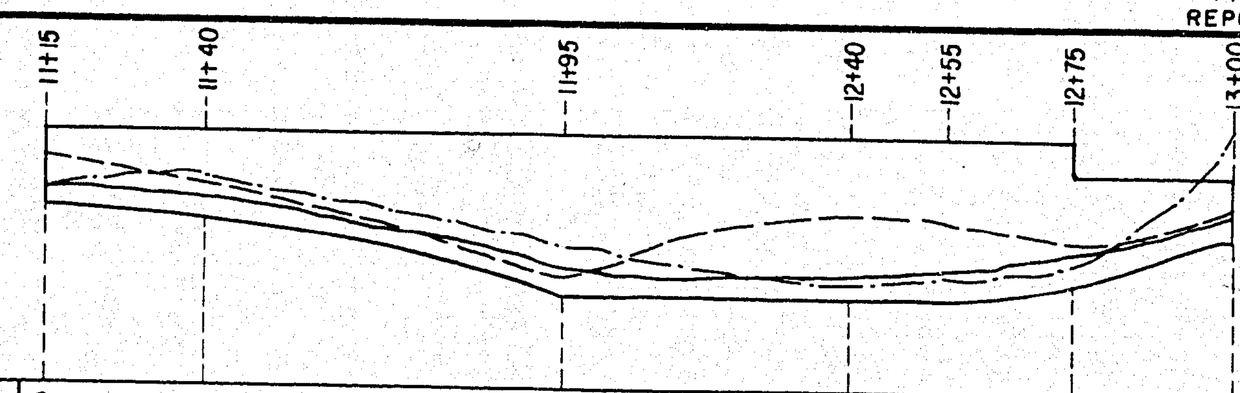


	11+15	11+45	11+95 / 12+00	12+40	12+55	12+75	13+00
Left	12	11	10	15	19	11	11
Center	NEAR CENTER 5	7	8	14	11	11	9
Right	7	12	10	9	9.5	11	11

PROFILE & DEPTH MEASUREMENTS IN FEET

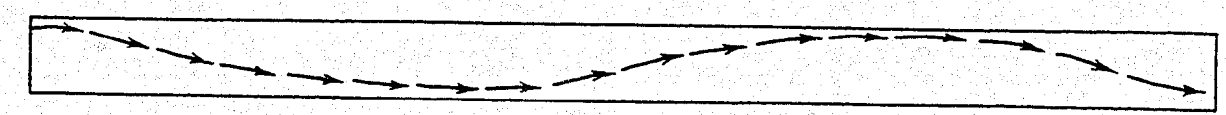


PLAN - MAIN FLOW Q= 7,200 C.F.S.

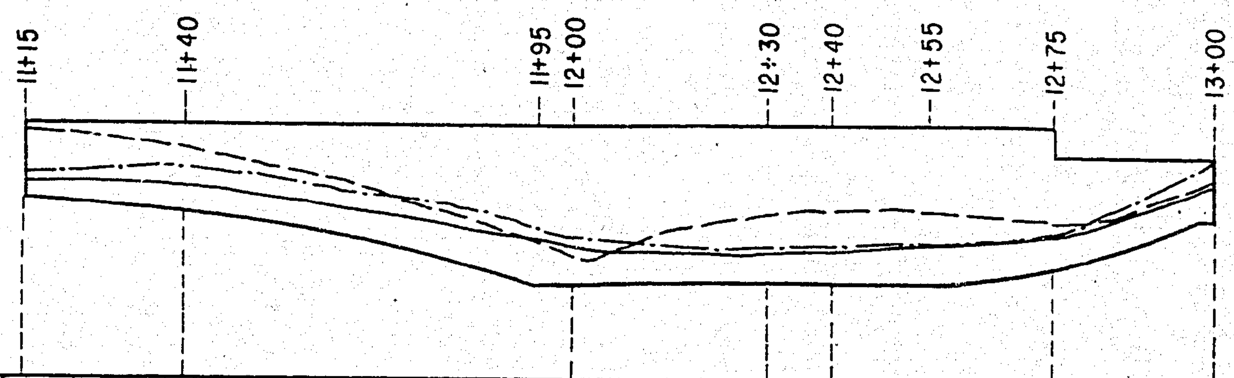


	11+15	11+40	11+95	12+40	12+75	13+00
Left	8	6	2.5	13	6	5
Center	3 NEAR CENTER	4	4.5	4	5	4
Right	3	7	8	3.5	3.5	17

PROFILE & DEPTH MEASUREMENTS IN FEET

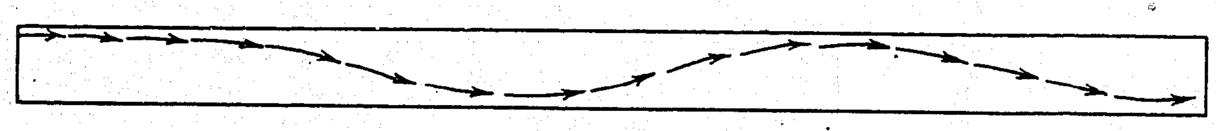


PLAN - MAIN FLOW Q= 3,000 C.F.S.

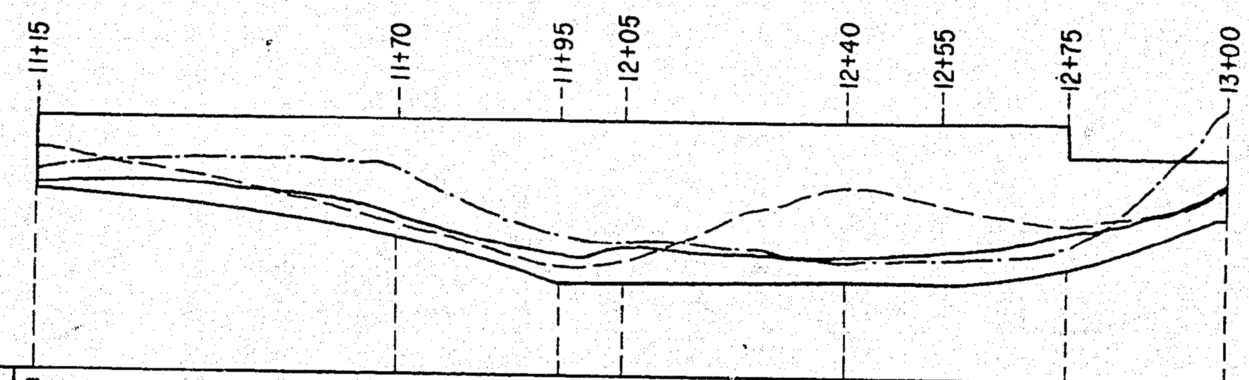


	11+15	11+40	12+00	12+30	12+75	13+00
Left	11	10	4	11	7	6
Center	NEAR CENTER 3	3	5.5	5.5	6	6
Right	4	7	7	6	6	10

PROFILE & DEPTH MEASUREMENTS IN FEET

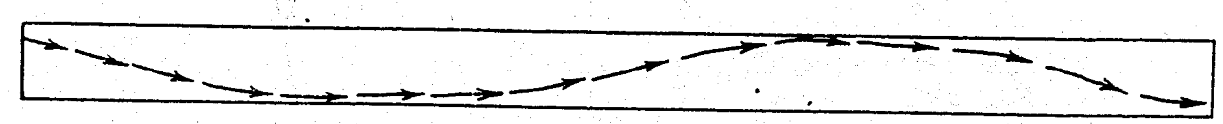


PLAN - MAIN FLOW Q=4000 C.F.S.



	11+15	11+70	11+95	12+05	12+40	12+75	13+00
Left	7	2.5	2	3	15	6	4
Center	1 NEAR CENTER	3	4	5	3	5	4
Right	3	11	7	6	3	3	18

PROFILE & DEPTH MEASUREMENTS IN FEET

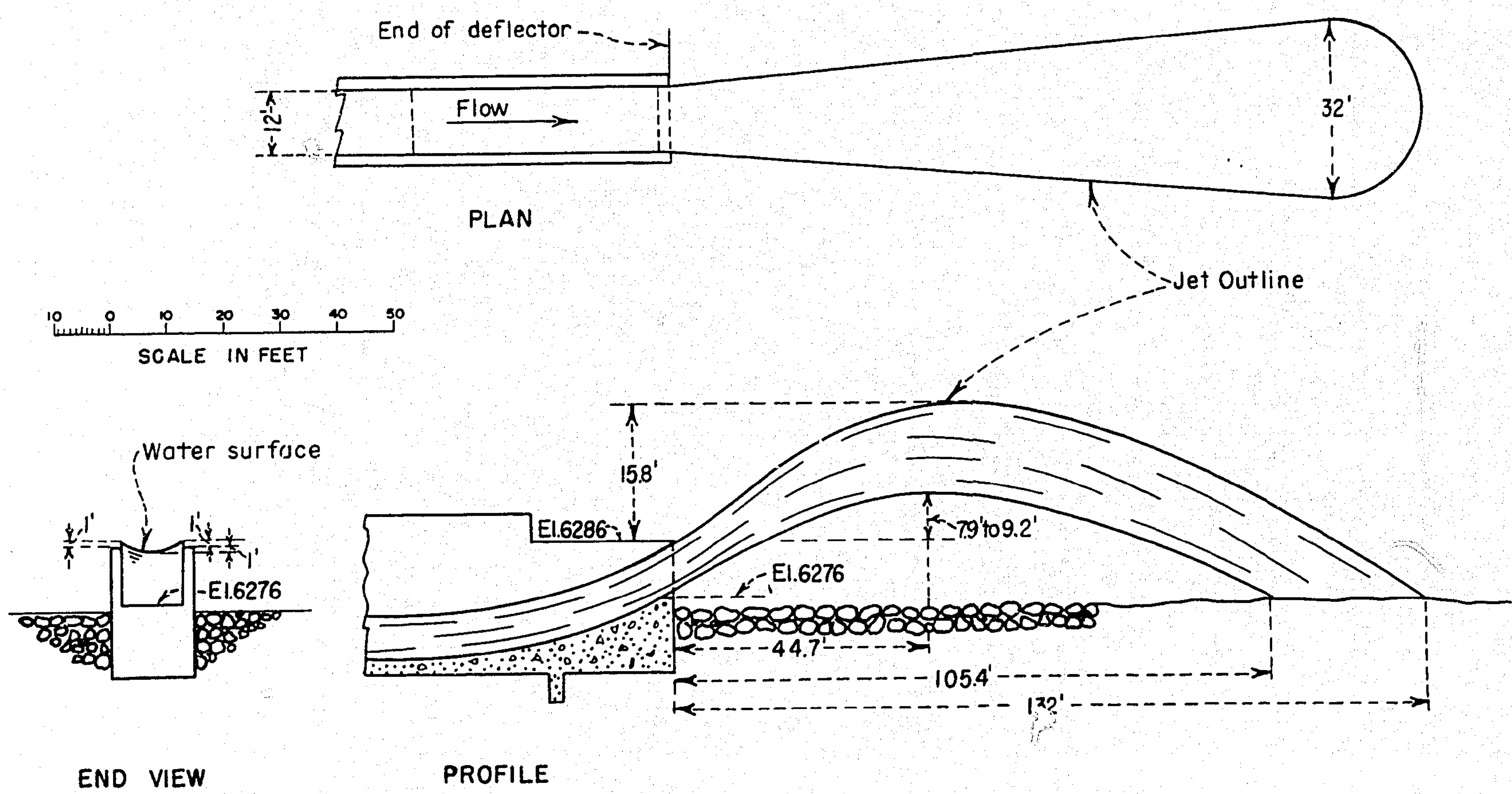


PLAN - MAIN FLOW Q= 2,500 C.F.S.

— — — — Water surface on left side
——— Water surface near center
— · — · — Water surface on right side

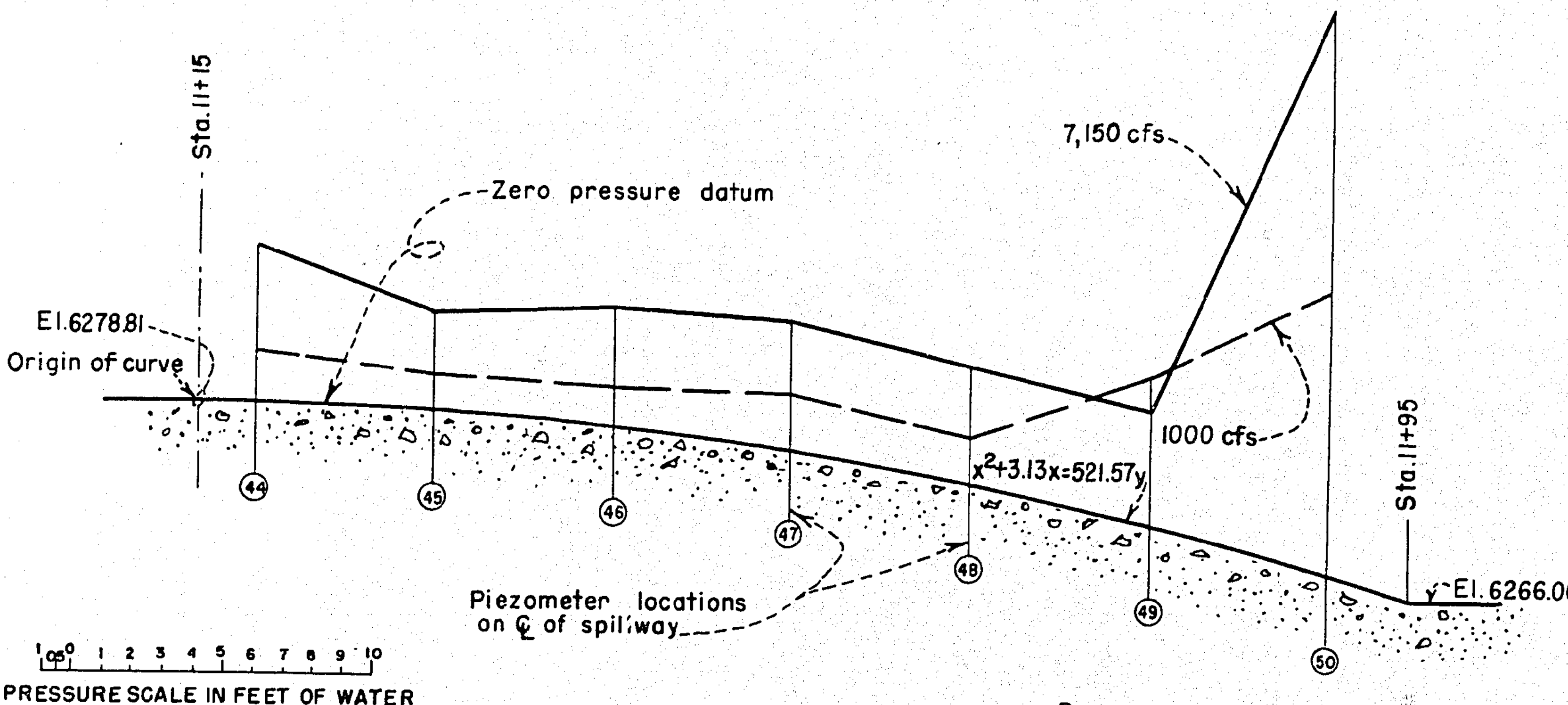
NOTE: Depths were measured vertically.

ANCHOR DAM SPILLWAY
WATER SURFACE IN STILLING BASIN
LARGE DISCHARGES
1:15.8 SCALE MODEL



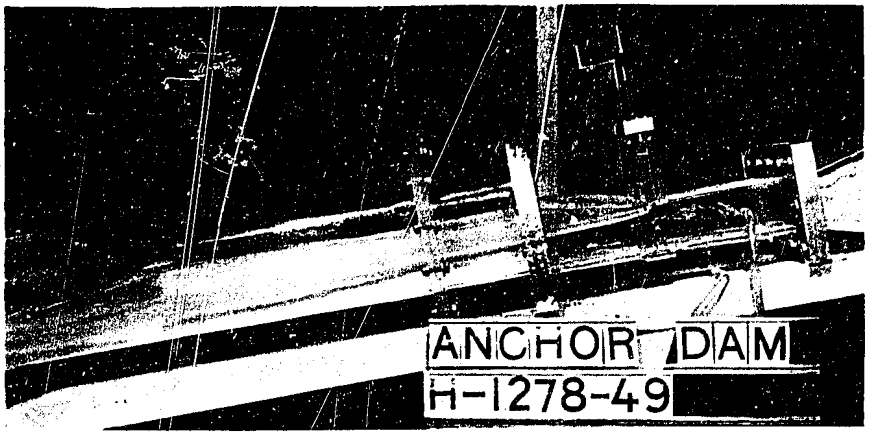
ANCHOR DAM SPILLWAY
SPILLWAY JET MEASUREMENTS
7,200 SECOND FEET
1:15.8 SCALE MODEL

FIGURE 35
REPORT HYD 437



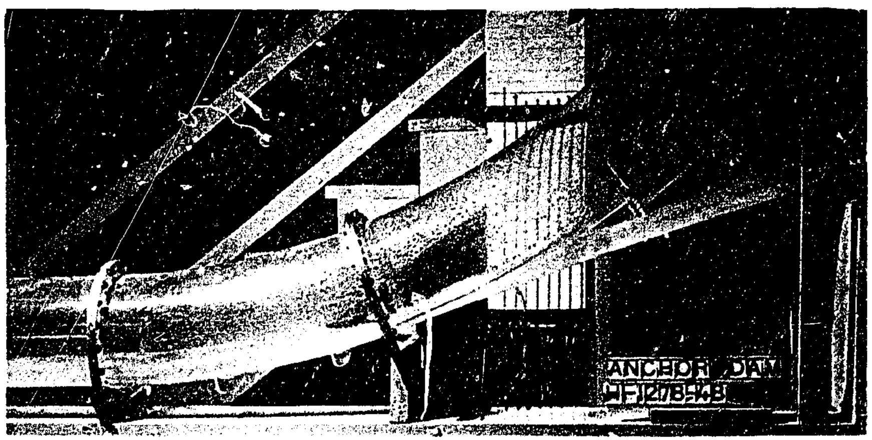
Pressures are above atmospheric and are plotted vertically upward from the datum.

ANCHOR DAM SPILLWAY
PRESSURES ON FLOOR OF STILLING BASIN
ENTRANCE TRAJECTORY
1:15.8 SCALE MODEL

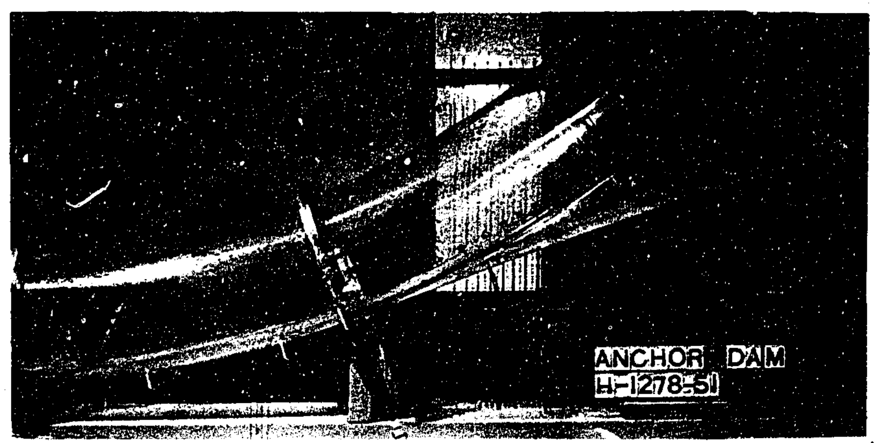


a. 640 second-feet
Gate open 87 percent
Reservoir elevation 6441 approximately

b. 300 second-feet
Gate open 49 percent
Reservoir elevation 6441 approximately



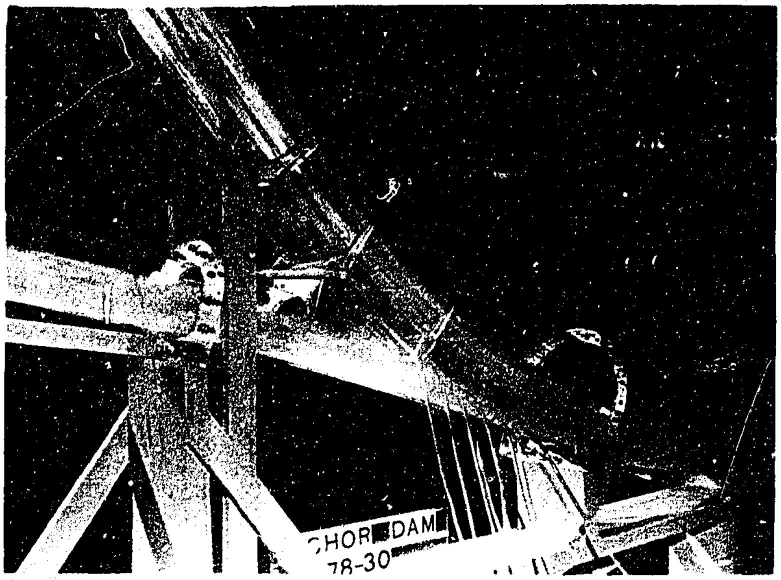
c. 640 second-feet



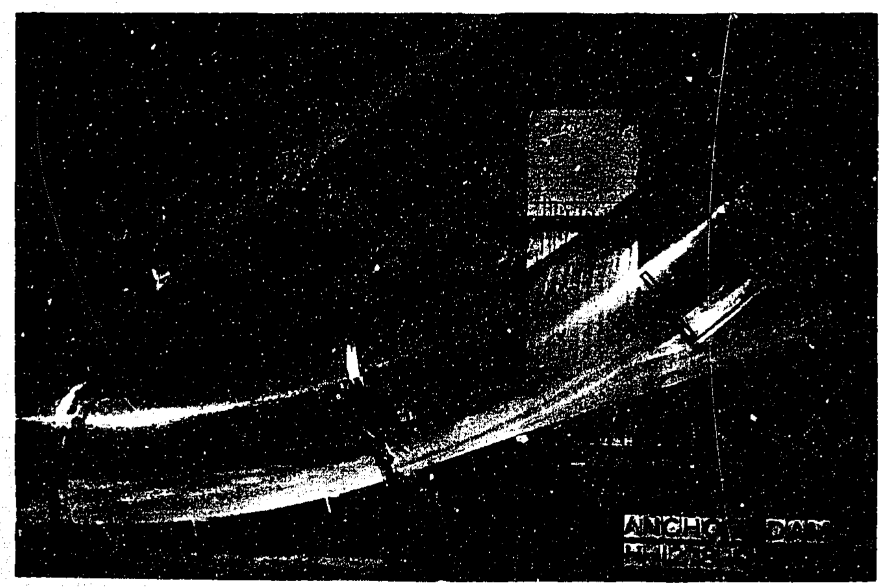
d. 300 second-feet

ANCHOR DAM SPILLWAY AND OUTLET WORKS
Outlet Works Discharging
1:15.8 Scale Model

Figure 37
Report Hyd-437

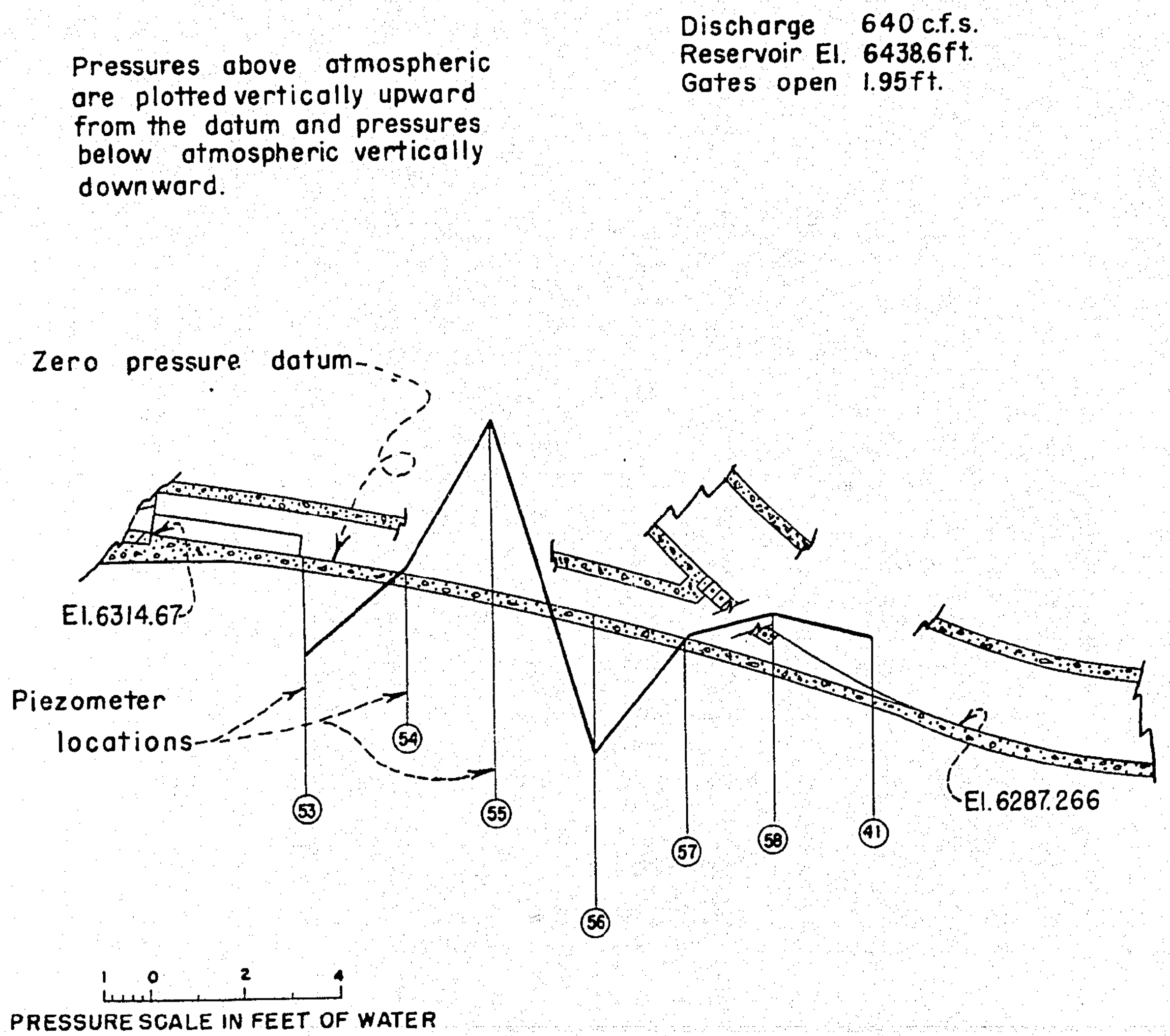


a. Spillway discharge--3,000 second-feet
Outlet works discharge--1,000 second-feet
Outlet works gates fully open (2.25 feet)

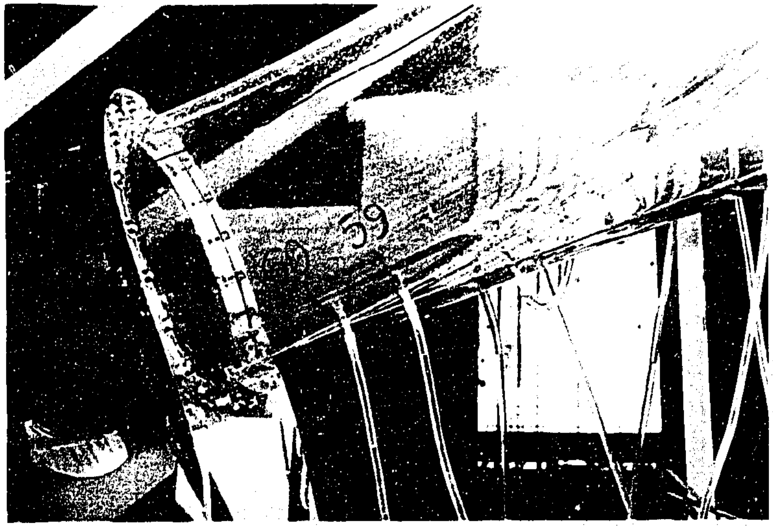


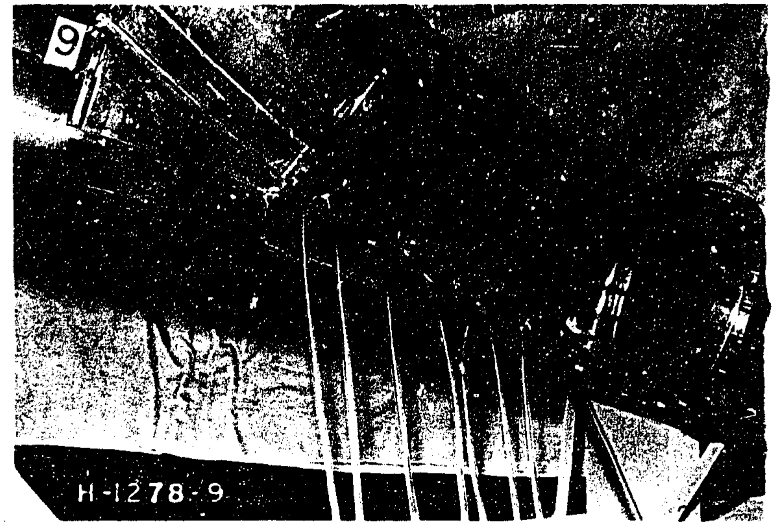
b. Spillway discharge--460 second-feet
Outlet works discharge--640 second-feet
Outlet works gates open 1.95 feet

ANCHOR DAM SPILLWAY AND OUTLET WORKS
Outlet Works and Spillway Discharging
Simultaneously
1:15.8 Scale Model



ANCHOR DAM OUTLET WORKS
PRESSURES ALONG THE OUTLET TUNNEL INVERT
1:15.8 SCALE MODEL





Discharge c.f.s.	Res. El. ft.	O.W. Gate opening %	Piezometers 34	35	36	37	38	39	40	41	42	43	59	60	Remarks
7,150	6460.47	closed	+20.0	+5.0	+8.0	+6.0	+31.0	+42.0	+50.0	+50.0	+30	+33			An added Piez. 6' U.S. from Piez. 41 showed a pressure fluctuation 0 to +5.0
1,000	6447.15	closed	- 0.1		- 0.6	+0.5	- 0.9	- 1.7	- 1.1	+ 0.9	+ 8.6	+11.4			
640	6433.8	100	0	0	0	-5.0	+ 2.5	- 1.9	- 0.8	- 1.0	+ 0.5	0			
640	6440.1	87	0	0	-0.5	-0.7	+ 0.9	- 1.5	- 0.6	- 1.3	- 5.0	+ 0.3			Pressure at Piez. No. 42 fluctuated from -1.7 to -5.0
640	6438.6	87	0	0	-0.5	-0.6	+ 0.2	- 1.3	- 0.3	+ 1.2	- 9.0	- 1.0	-0.2	-3.1	Pressure at Piez. No. 42 fluctuated from -2.0 to -9.0
300	6437.3	49			0	0	0	0	- 0.5	+ 0.8	- 2.8	- 1.0	+0.2	-2.8	
Piez. location in feet from joining edge of tunnels			1.0	0.6	1.0	0.2	0.7	0.3	0.5		0.2	0.2	0.2	0.1	Piez. s 34, 59 & 60 are on the spillway floor. Others are on the outlet wks. wall.

Pressures are in feet of water. Zero pressure is atmospheric pressure.

ANCHOR DAM SPILLWAY AND OUTLET WORKS
Pressures In Outlet Works Tunnel & Spillway Tunnel Junction
1:15.8 Scale Model

Figure 40
Report Hyd-437